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ADVANCED COMPOSITE ARMY ASSAULT BRIDGE DEVELOPMENT THROUGH SUBC--ETC(U)

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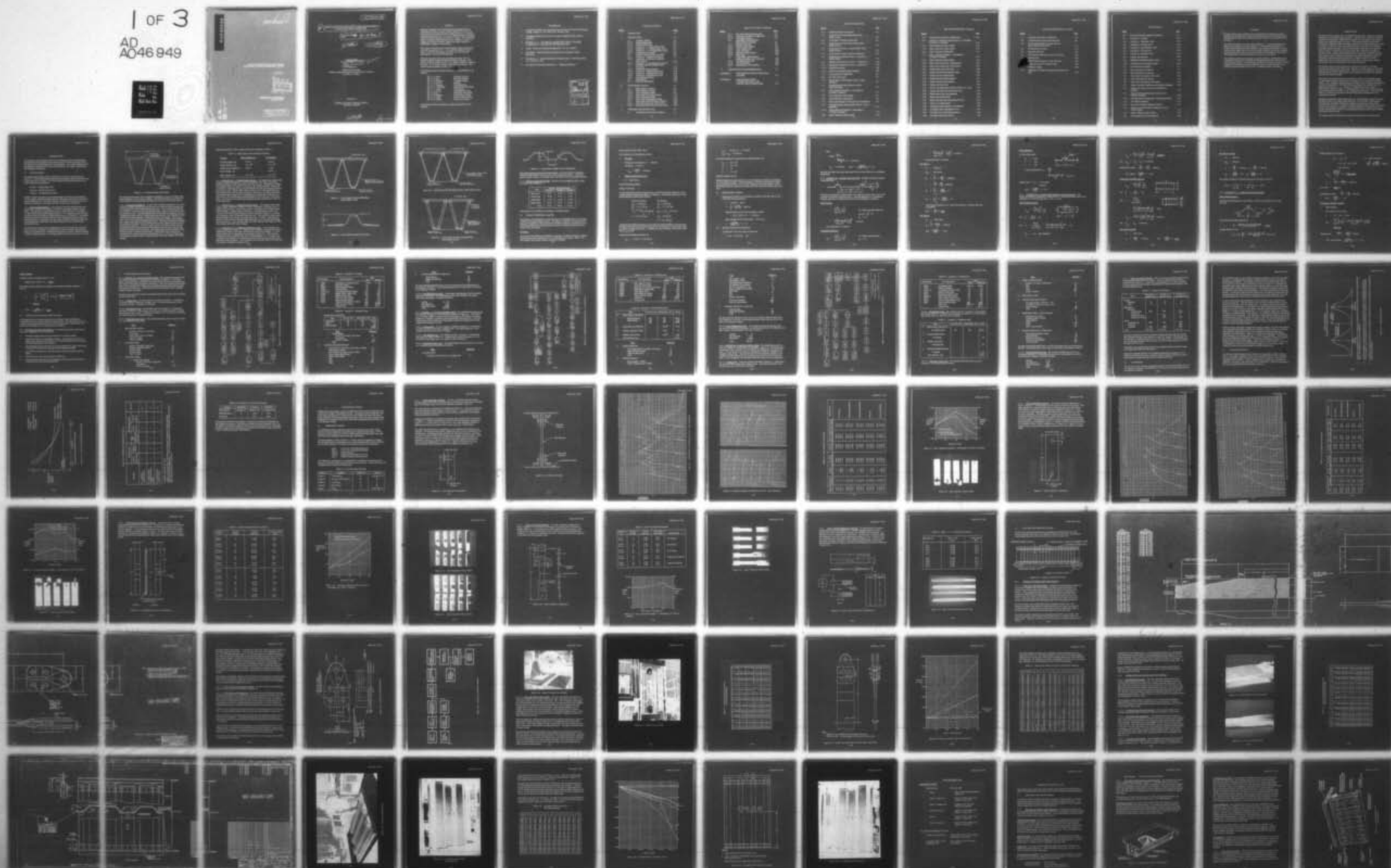

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ADVANCED COMPOSITE ARMY ASSAULT BRIDGE DEVELOPMENT THROUGH SUBCOMPONENT TESTING,

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San Diego, California

147650

PREFACE

Advanced Composite Army Assault Bridge Development Through Subcomponent Testing, Contract Number DAAG53-76-C-0175, was carried out by the Convair Division of General Dynamics Corporation under the sponsorship of the U. S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia. The Contracting Officer's Technical Representative was Mr. William R. Sutton, Jr., Bridge and Structures Division, Marine and Bridge Laboratory — DRXFB-MD, Telephone (703) 664-5176.

This report is the final report summarizing the entire program from June 1976 through March 1977. It is intended to fulfill the requirements of Form DD 1423, Sequence Number A009 and Data Item Description No. DI-S-1800 with addendum.

This work was performed by the Composite Structures Group of General Dynamics Convair Division, San Diego, California. This group is under the direction of Mr. D. R. Dunbar, within the organization of Mr. J. D. Forest, Director of Structures and Design. The Convair program manager was Mr. F. H. [illegible].

The following Convair personnel made signi[illegible]t contributions to the program:

Mr. R. S. Wilson	Structural Analysis
Mrs. A. Tanke	Structural Analysis
Mr. J. E. Burgeson	Conceptual Design
Mr. L. M. Moore	Drafting
Mr. P. T. Kaneyuki	Tool Engineering
Mr. R. C. Christopher	Manufacturing Technology
Mr. J. S. Comber	Cost Analysis
Mr. G. L. Olson	Corrugated Panel Fab.
Mr. J. Hertz	Tension Cap Fabrication
Mr. C. R. Maikish	Test Article Assembly
Mr. N. R. Adsit	Coupon & Panel Testing
Mr. R. W. Gilbert	Tension Cap Testing

The following reference material was used in the execution of this program.

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1. "Advanced Composite Army Assault Bridge Development Through Subcomponent Testing," Report No. GDC CM76-013B, February 1976.

2. "Trilateral Design and Test Code for Military Bridging and Gap Crossing Equipment."

3. Kaminsky, B. E., "Development of Design Data for Narmco T300/5208 Graphite-Epoxy," GDC-ERR-FW-1524, December 1973.

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7. GD/Fort Worth Structures Manual Vol. I, "Methods of Analysis."

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SUMMARY

The basic purpose of this program was to demonstrate that advanced composite materials can be applied to the main load carrying elements of an armored vehicle launched assault bridge with a significant saving in weight over metallic structural materials.

The study was carried out in three major segments: 1. A conceptual design and analysis concentrating on the shear panels; 2. A subelement test program to develop basic laminate and joint allowables to aid in design and analysis of critical portions of the bridge; also a test of two full scale composite test articles representing the critical joint areas in the selected concept; and 3. Design of a three meter lightweight bridge test section applying the results of 1 and 2 above.

Basic analysis methods and assumptions regarding boundary conditions and stress concentration factors used in stability and strength analyses were verified by the structural test program. The final design resulted in a composite AVLB test section weighing 125.7 Kilograms/meter including the upper deck and all fittings. This indicates significant weight savings over a comparable design in aluminum.

INTRODUCTION

The purpose of this program was to investigate the application of advanced composite materials to Army assault bridge structures. Advanced, fiber reinforced composite materials have undergone considerable development over the past ten years and are seeing more widespread usage every year. The original emphasis was placed on development of high performance aerospace hardware where high material costs could be justified or tolerated. Now, the rapidly advancing state of the art in advanced composite structures coupled with the recent dramatic reductions in raw material costs has made it economical to use these "space-age" materials in a number of industrial areas. Weight reductions approaching 40 percent have been achieved in the past for entire wing structures through the use of advanced composite materials. This potential weight reduction and improved performance attainable through the application of advanced composite materials to bridging structures will help MERADCOM meet its technical objectives of the 1980s: increased span, reduced construction time, and commonality of structural components.

The specific objective of this program was to develop the design of a 3-meter composite test section (CTS) which could constitute the center section of a 22-meter armored vehicle launched bridge (AVLB). The CTS was to be designed to mate with existing aluminum AVLB ramp sections and be capable of surviving 15,000 military load class 60 vehicle crossings.

The program was divided into three major tasks or phases; (1) Conceptual Design; (2) Subcomponent Design, Fabrication, and Testing; and (3) Composite Test Section Design. In the conceptual design phase of the program, three composite bridge design concepts were generated. The basic difference between these concepts was in the shear panel construction, i.e., Concept 1 — Beaded Shear Panel; Concept 2 — Sandwich Shear Panel; Concept 3 — Corrugated Shear Panel. These design concepts were then evaluated on the basis of cost, weight and producibility. At the end of this phase, one concept was selected for further development and application to the composite Test Section.

During the development article design phase, the selected design concept was refined and detail design of the critical areas performed. Two full scale subcomponents were designed, fabricated and tested to evaluate the performance of the critical elements of the structure. Following successful completion of the testing, the composite test section design was finalized. A manufacturing and cost analysis of the test section was performed to develop a manufacturing sequence and flow plan and identify associated fabrication costs.

The chapters that follow discuss the program accomplishments in greater detail.

2

CONCEPT STUDY

The objective of the concept study task was to generate several composite design concepts that could be applied to the substructure of the 3-meter composite AVLB test section to be detail designed later in the program. One of these concepts would be selected for application to the test section based on cost, weight, producibility, and reliability assessments.

2.1 CONCEPT DESIGN

The bridge design concepts all have basically the same "W" cross-section (see Figure 2.1). An extruded aluminum upper deck and graphite/epoxy lower tension cap were baseline for all concepts. The major differences between the concepts were in their shear panel construction:

Concept 1 - Beaded Shear Panel

Concept 2 - Sandwich Shear Panel

Concept 3 - Corrugated Shear Panel

Primary emphasis was placed on conceptual design of the shear panels since they were the largest composite members and they represent a major portion of the test section weight and cost. The tension fittings, end bulkheads, and lower deck were considered identical for all concepts and their details were not addressed.

2.1.1 <u>DESIGN REQUIREMENTS</u>. The composite AVLB test section design must comply with a number of dimensional, structural, and damage tolerance requirements. The test section constitutes the center 3-meter section for one treadway of a total bridge span of approximately 22 meters. It is required to mate with existing ramp sections according to MERADCOM Drawing No. 13216E8001. The primary interface between the test section and the ramp is the pinned connection of the two lower tension caps. Secondarily, the upper deck of the test section must align with and bear against the upper deck of the ramp sections in order to transmit deck compression loads.

The composite test section must be designed to survive 15,000 military load class (MLC) 60 vehicle crossings. The applied loads, factors of safety, and deflection limits are as specified in the "Trilateral Design and Test Code for Military Bridging and Gap Crossing Equipment." The design thermal environment is from -65 to 160F.

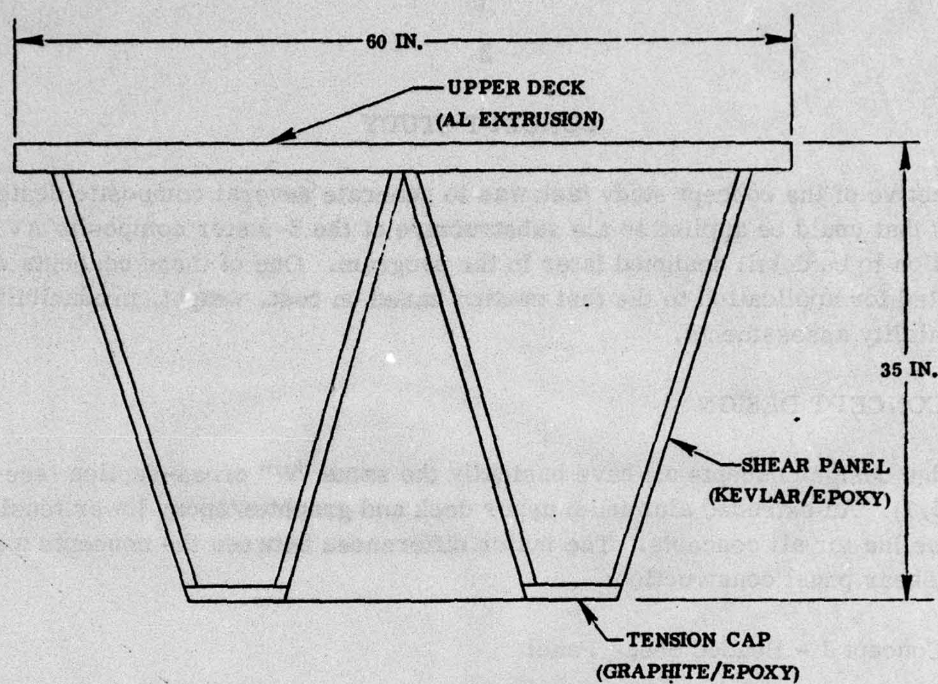


Figure 2.1. Composite Bridge Cross-Section

The composite test section must be capable of sustaining 1.5 times the design loads after penetration by a 50-caliber projectile. This ballistic damage is considered to be the maximum survivable threat encountered by the AVLB on an assault mission.

2.1.2 COMPOSITE MATERIALS. As part of the conceptual design task, a survey of available composite material systems was made in an effort to identify systems that could significantly reduce bridge manufacturing costs. Price quotes were obtained for various low cost Kevlar/epoxy and graphite/epoxy systems in both unidirectional tape and fabric forms. Although graphite/epoxy fabrics offered significant reductions in handling and layup costs over unidirectional tape material, the substantially higher material cost greatly reduced or eliminated the labor cost savings. This was not true, however, for Kevlar/epoxy systems where the fabric material was available at lower cost per pound than the unidirectional tapes. The Kevlar/epoxy fabrics offered the advantage of being the lowest cost advanced composite material system available with minimum layup time. It must be noted, however, that Kevlar/epoxy material properties in shear and compression are somewhat lower than those of G/E so that greater thicknesses would be required. This weight penalty would be partially offset by Kevlar/epoxy's 15 percent lower density. Kevlar/epoxy fabric material was proposed for use in the composite test section shear webs. The lower tension caps were designed in graphite/epoxy to take advantage of its higher stiffness and bearing strength.

Typical properties for these material systems are presented in Table 2-1.

Table 2-1. Kevlar/Epoxy Fabric Material Properties

Property	Warp Direction (0°)	45° Direction
Tensile Strength, psi	73,000	30,000
Tensile Modulus, psi	4.0×10^6	1.1×10^6
Compression Strength, psi	21,000	9,750
Shear Strength, psi	—	32,000
Shear Modulus, psi	0.3×10^6	3.0×10^6

2.1.3 CONCEPT NO. 1 — BEADED SHEAR PANEL. The beaded shear panel bridge concept, illustrated in Figure 2.2, has four diagonal Kevlar/epoxy shear panels extending between the upper deck and the lower tension caps. The panels are stiffened by integral beads (see Figure 2.3) running in the vertical direction. Extra plies are added for reinforcement along the panel edges where they join the upper deck and lower tension caps. The four shear panels are laid up on a "W" shaped tool along with the tension caps and the entire assembly is cured into a one-piece substructure. The graphite/epoxy tension caps are encapsulated by Kevlar/epoxy cloth from the shear panels, thus eliminating mechanical fasteners at the lower cap to shear panel joints. The beads are cut and formed separately and then positioned over cutouts in the flat panel layup.

2.1.4 CONCEPT NO. 2 — SANDWICH SHEAR PANEL. The sandwich shear panel bridge concept, illustrated in Figure 2.4, has a substructure consisting of two "V" shaped composite beams. Each of these beams is comprised of two sandwich shear panels attached to a graphite/epoxy tension cap. The shear panels consist of two .080-inch thick Kevlar/epoxy facings cocured and adhesively bonded to a 1.25-inch thick fiberglass reinforced phenolic honeycomb core. The sandwich facings encapsulate the graphite/epoxy tension cap at the apex of the "V" section. Extra plies are added for reinforcement of the panel edges where they join to the upper deck flange and the tension cap. Also, the honeycomb core cells along the panel edges are filled with potting compound for added strength.

2.1.5 CONCEPT NO. 3 — CORRUGATED SHEAR PANEL. The corrugated shear concept, illustrated in Figure 2.5, consists of four separate corrugated shear panels mechanically fastened to the upper deck and lower tension cap members. A cross-section through the corrugated panel is presented in Figure 2.6. This particular configuration yields a material wrap factor of approximately 1.15. The caps of the corrugations are attached to the upper deck extrusion and lower cap members using industrial huckbolt fasteners. The corrugations will be potted locally at the upper and lower edges to stabilize the diagonal webs.

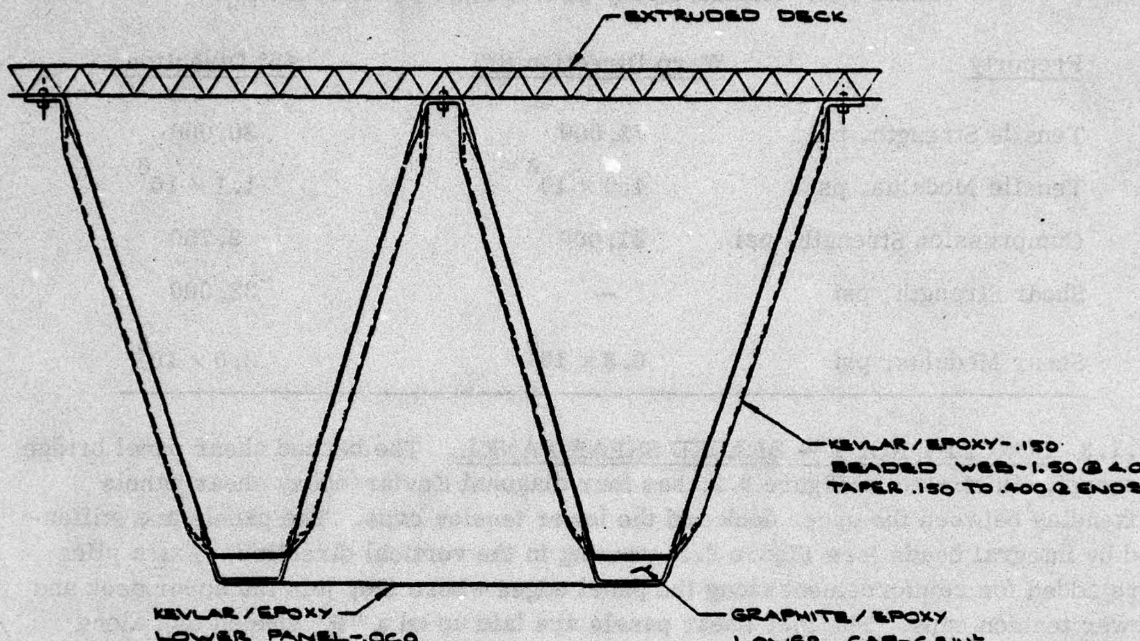


Figure 2.2. Cross-Section Through Beaded Shear Panel Bridge Concept

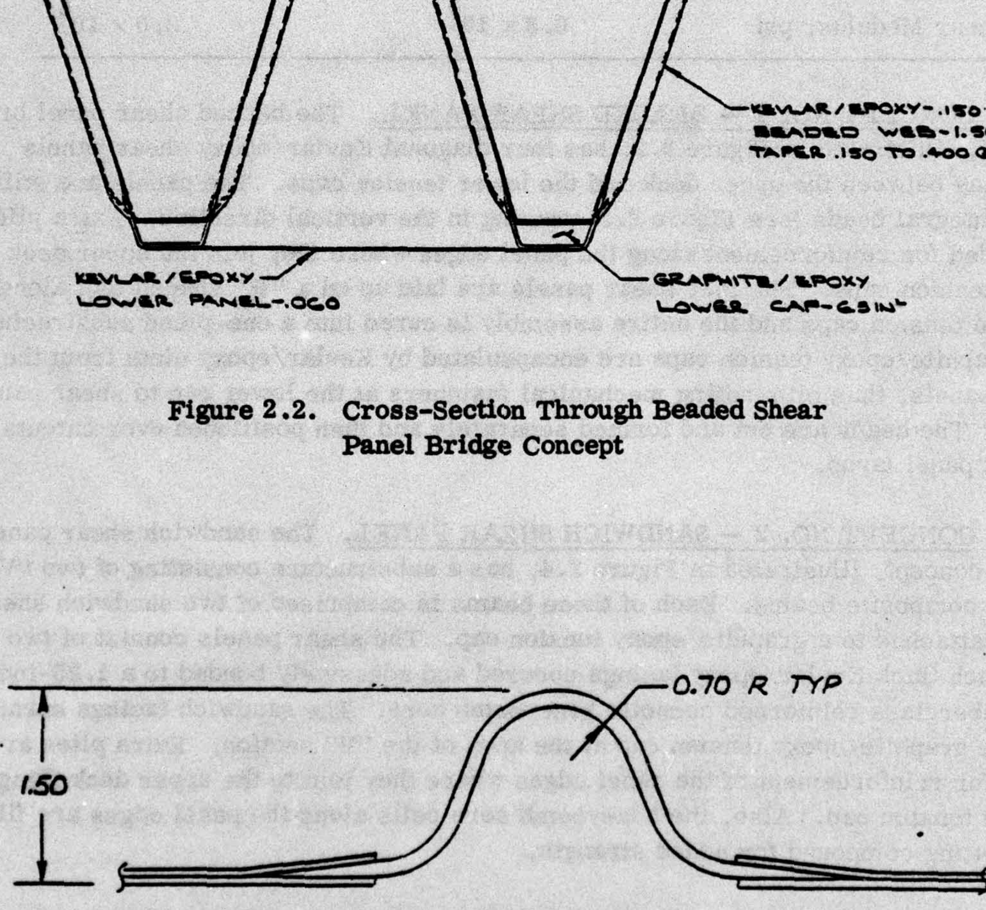


Figure 2.3. Cross-Section Through Typical Bead

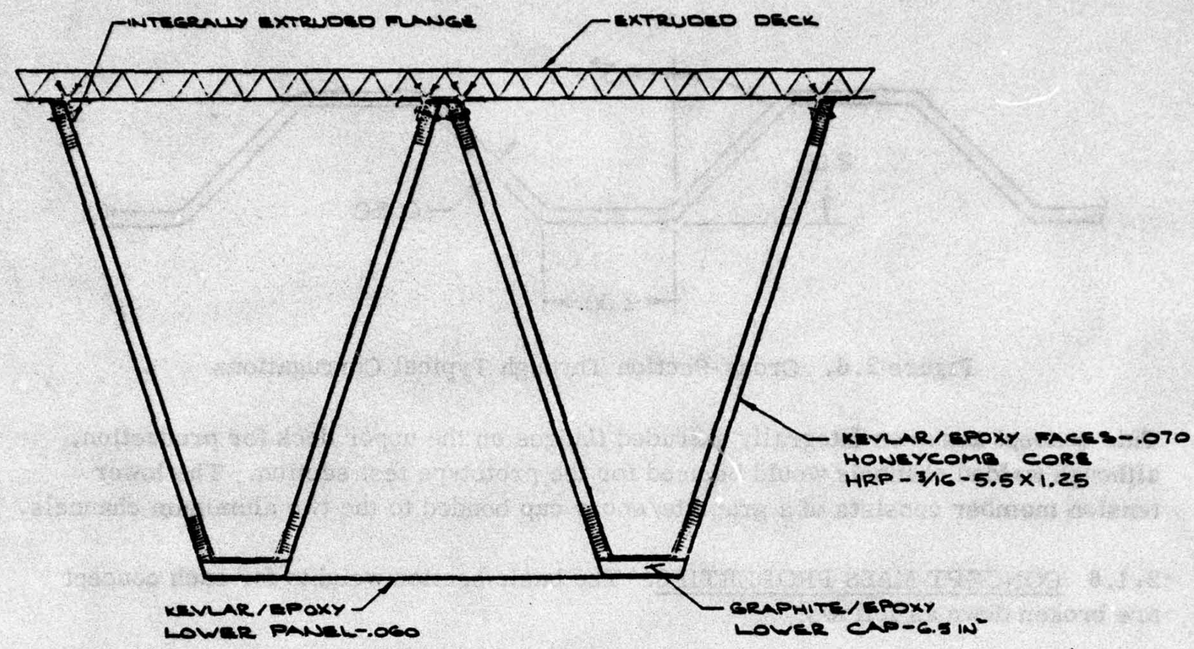


Figure 2.4. Cross-Section Through Sandwich Shear Panel Bridge Concept

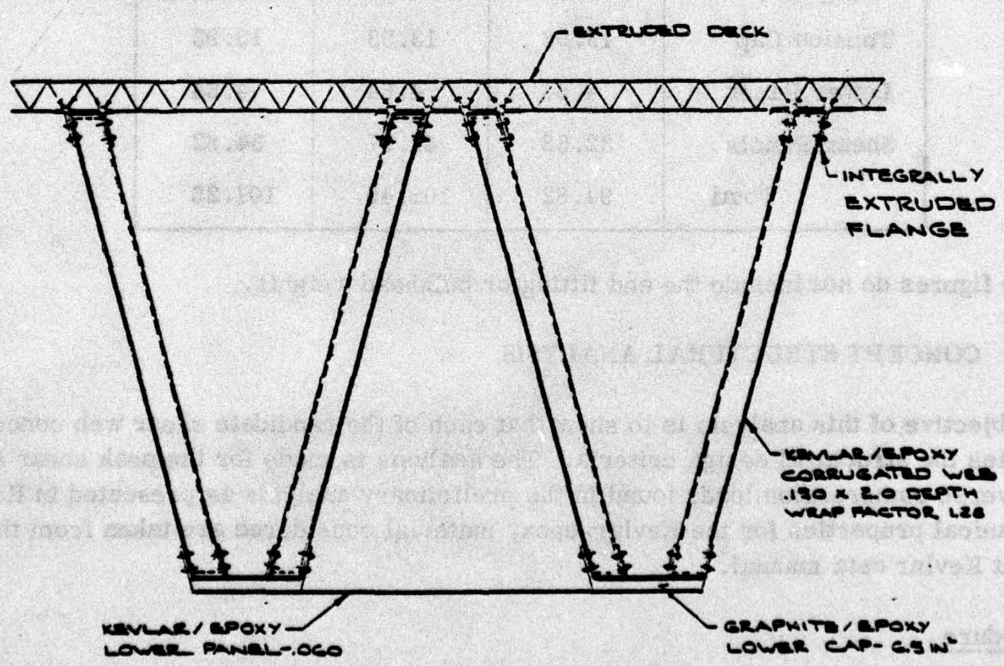


Figure 2.5. Cross-Section Through Corrugated Shear Panel Bridge Concept

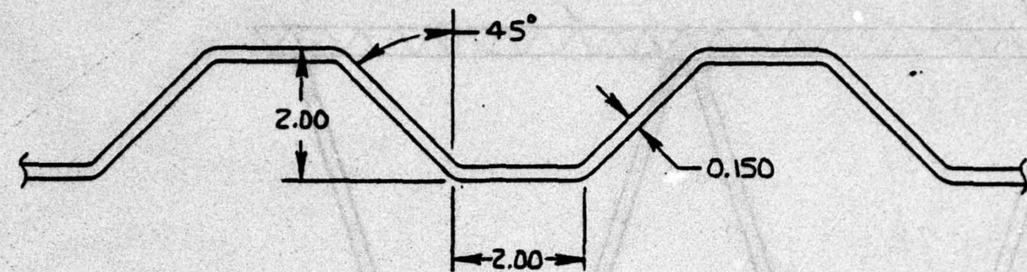


Figure 2.6. Cross-Section Through Typical Corrugations

This concept assumes integrally extruded flanges on the upper deck for production, although welded channels would be used for the prototype test section. The lower tension member consists of a graphite/epoxy cap bonded to the two aluminum channels.

2.1.6 CONCEPT MASS PROPERTIES. The basic section weights for each concept are broken down as follows:

Item	Weight - Kilograms/Meter		
	Concept 1	Concept 2	Concept 3
Upper Deck	43.57	47.86	47.86
Tension Cap	13.93	13.93	13.93
Lower Panel	4.64	4.64	4.64
Shear Panels	32.68	41.97	34.82
Total	94.82	108.40	101.25

These figures do not include the end fitting or bulkhead weights.

2.2 CONCEPT STRUCTURAL ANALYSIS

The objective of this analysis is to show that each of the candidate shear web concepts satisfies the structural design criteria. The analysis is made for the peak shear and transverse compression loads found in the preliminary analysis as presented in Ref. 1. Mechanical properties for the Kevlar/epoxy material considered are taken from the Dupont Kevlar data manual.

Procedure

The required web thickness is established on the basis of ultimate strength considering ballistic damage due to penetration of a 0.5-inch diameter projectile. Hence, with this thickness each design concept is analyzed for stability.

Design Loads for Shear Webs, Ref. 1

Two conditions were considered as follows:

1. 60T Tank

Transverse compression (w') = 334 lb/in

Max Shear = 11,834 lb.

$$\therefore \quad N_{xy} = \frac{11,834}{31} = 382 \text{ lb/in}$$

2. Maximum Single Wheel Load

w' = 492.2 lb/in

Kevlar Epoxy Shear Panels

Material Properties

For this preliminary study a pseudoisotropic $(0/\pm45/90)_s$ laminate made from 8 plies of balanced weave Kevlar/epoxy fabric is considered. The lamina properties from the Kevlar materials manual are as follows:

Warp (0°) direction	45° Direction
F_{tu} = 73,000 psi	F_{tu} = 30,000 psi
E_T = 4.0×10^6 psi	E_T = 1.1×10^6 psi
$F_{c_{.2}} = 1.5\ F_{c_{.2}}$ = 21,000 psi	$F_{cu} = 1.5\ F_{c_{.2}}$ = 9,750 psi
G = 0.30×10^6 psi	F_{su} = 32,000 psi
	G = 3.0×10^6 psi

Conservative strength properties for the $(0/\pm45/90)_s$ laminate, based on the assumption the axial (0/90) plies carry all axial loads and the ±45° fibers carry all the shear loads, are used in the following analysis. In addition for shear buckling a cutoff stress equal 50% of F_{cu} is used.

Therefore the laminate properties are

$$F_{tu} = 73,000 \times .5 = 36,500 \text{ psi}$$

$$F_{cu} = 21,000 \times .5 = 10,500 \text{ psi}$$

$$F_{su} = F_{cu} = 10,500 \text{ psi}$$

The elastic properties as determined by laminate analysis are:

$$E_x = 2.9 \times 10^6$$

$$E_y = 2.0 \times 10^6$$

$$\nu = .31$$

$$G = 1.1 \times 10^6$$

Ballistic Damage Analysis

Ballistic damage due to penetration by a 0.5-inch diameter projectile is considered for preliminary evaluation. The local damage is represented by theoretical elastic stress concentration factors of 4 for shear loading and 3 for axial loading. These theoretical values are conservative; actual tests show values about half of those used here.

A. Maximum Shear Condition

Assuming all the shear in the laminate is carried by this ±45° plies (or 50% of the total laminate thickness)

$$S = 11,834 \text{ lb.} \quad \text{Ref. 1}$$

$$\tau = \frac{S}{ht} = \frac{11,834}{31 \times .16} = 2386 \text{ psi}$$

Maximum Shear in ±45° Plies at Damage Location

$$= 2\,K_T = 2386 \times 2 \times 4 = 19.088 \text{ psi}$$

Shear Strength of ×45° Kevlar Epoxy = 32,000 psi

$$\therefore \quad \frac{32,000}{19088 \times 1.5} -1 = +.12$$

B. Maximum Transverse Compression

Assuming the 0°-90° plies carry all axial load

$$w' \text{ max} = 492.2 \text{ lb/in} \quad \text{Ref. 1}$$

Then

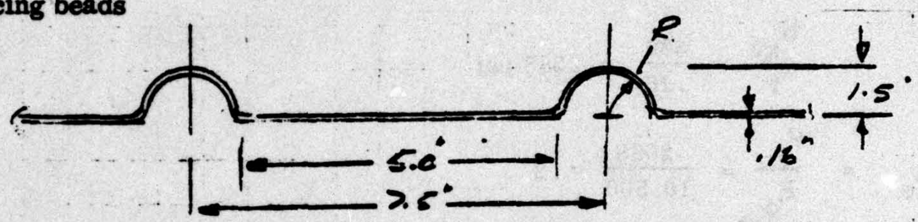
$$\sigma_{max} = \frac{2w}{t} K_T$$

$$= \frac{492.2 \times 2}{.16} \times 3 = 18,457 \text{ psi}$$

$$F_{cu} = 25,000 \text{ psi} \quad \therefore \text{ M.S.} = \frac{25,000}{18,457 \times 1.5} - 1 = -.10$$

Since the ±45° fibers will carry more than 10% of the load, this M.S. is considered satisfactory.

2.2.1 CONCEPT NO. 1 BEADED WEB ANALYSIS. Buckling of flat panel between reinforcing beads



The panel is analyzed for combined shear and compression from Case 1 and for the maximum compression load from Case 2. Buckling equations for a homogeneous isotropic material are sufficiently accurate for this preliminary evaluation.

Shear Buckling

$$\tau = \frac{K_s \pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2$$

For simply supported edges and

and $a/b = \frac{31}{5} = 6.2$

$K_s = 5.8$

$$= \frac{5.8^2 \times 2.9 \times 10^6}{12(1-.31^2)} \left(\frac{.16}{5}\right)^2 = 15,672 \text{ psi}$$

Use cutoff stress = 10,500 psi

Compression Buckling

$$\sigma_{cr} = \frac{K_c \pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2$$

For simply supported edges

$K_c = 4.0$

$$= \frac{4^2 \times 2.9 \times 10^6}{12(1-.31^2)} \left(\frac{.16}{5}\right)^2 = 10,808 \text{ psi}$$

Use cutoff stress = 10,500 psi

For Case #1

$N_y = -334$ lb/in

$N_{xy} = 382.0$ lb/in

$$\therefore \quad \sigma_y = \frac{N_y}{t} = \frac{-334}{.16} = -2088 \text{ psi}$$

$$\tau = \frac{N_{xy}}{t} = \frac{382}{.16} = 2388 \text{ psi}$$

$$R_c = \frac{\sigma_y}{F_{c_{cr}}} = \frac{2088}{10,500} = .2$$

$$R_s = \frac{\tau}{F_{s_{cr}}} = \frac{2388}{10,500} = .23$$

$\therefore$ From General Dynamics F.W. Structures Manual for combined shear and compression

$$\text{M.S.} = \frac{.93}{.20} - 1 = \underline{+3.65}$$

For Case #2

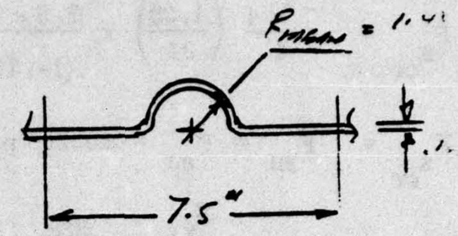
$N_y = -492.2$ lb/in

$$\therefore \quad \sigma_y = \frac{N_y}{t} = \frac{492.2}{.16} = -3076 \text{ psi}$$

$$\therefore \quad \text{M.S.} = \frac{10,500}{3076} - 1 = +2.41$$

<u>Column Buckling</u>

For the section shown



$A = 1.459$

$\bar{y} = .483$

$I = .384$

$\therefore$ Column buckling load $P_c = \dfrac{\pi EI}{L^2}$

$$= \frac{\pi^2 \times 2.9 \times 10^6 \times .384}{30^2} = 12{,}221 \text{ lb.}$$

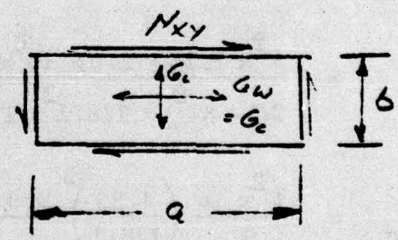
Applied Load $= 7.5\,w' = 7.5 \times 492.2$

$= 3691$ lb

$\therefore$ M.S. $= \dfrac{12{,}221}{3691} - 1 = +2.3$

2.2.2 <u>CONCEPT NO. 2: HONEYCOMB SANDWICH PANEL ANALYSIS</u>. The honeycomb sandwich considered is comprised of two .08 pseudoisotropic Kevlar/epoxy facesheets on a 1.25-inch thick HRP - 3/16 - 5.5 core.

<u>Shear Buckling Analysis</u>



$$F_{s_{cr}} = \frac{\pi^2 K_s}{4}\left(\frac{t}{b}\right)^2 \frac{E}{1-\nu^2}$$

For $\dfrac{b}{a} = \dfrac{31.0}{118.1} = .26$

and $V = \dfrac{\pi^2 t_c Et}{a(1-\nu^2)b^2 G_c} = \dfrac{\pi^2 \times 1.25 \times 2.9 \times 10^6 \times .08}{2(1-.31^2) \times 31^2 \times 8500} = .19$

$K_s = 4.0$ (MIL-HDBK-23)

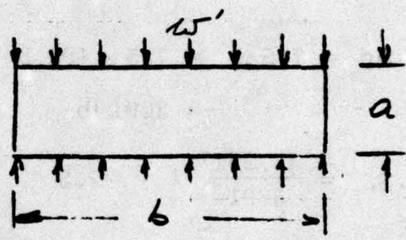
$$\therefore \quad F_{s_{cr}} = \frac{\pi^2 \times 4}{4}\left(\frac{1.33}{31}\right)^2 \times \frac{2.9\times 10^6}{(1-.31^2)} = \underline{\underline{58,536}} \text{ psi}$$

$$\text{Use} \quad F_{s_{cr}} = F_{su} = F_{cu} = 10,500 \text{ psi}$$

$$\text{Applied shear stress} = \frac{N_{xy}}{2t} = \frac{382}{.16} = 2388 \text{ psi}$$

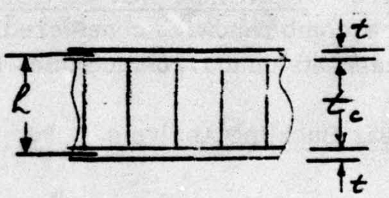
$$\therefore \quad \text{M.S. (shear)} = \frac{10,500}{2388} - 1 = +3.39$$

<u>**Compression Buckling Analysis**</u>



$$F_{c_{cr}} = \frac{\pi^2 K}{4}\left(\frac{h}{b}\right)^2 \frac{F_2}{(1-\nu^2)}$$

$$\text{For} \quad \frac{a}{b} = \frac{31}{118.1} = .26$$



$$\text{and} \quad V = \frac{\pi^2 t_c e t}{2(1-\nu^2) b^2 G_c}$$

$$= \frac{\pi^2 \times 1.25 \times 2.9 \times 10^6 \times .08}{2(1-.31^2)\times 118.1^2 \times 19500} = .0058$$

$$\therefore \quad F_{c_{cr}} = \frac{\pi^2 \times 14}{4}\left(\frac{1.33}{118.1}\right)^2 \frac{2.9\times 10^2}{(1-.31^2)} = 14055 \text{ psi}$$

$$\text{Use} \quad F_{c_{cr}} = F_{cu} = 10500 \text{ psi}$$

<u>**For Case #2 Loading**</u>

$$w' = 492.2 \text{ lb/in}$$

$$\therefore \quad f_c = \frac{492.2}{.16} = 3076 \text{ psi} \qquad \therefore \quad \text{M.S.} = \frac{10500}{3076} - 1 = \underline{\underline{+2.41}}$$

For Case #1 Loading

$$w' = 334 \text{ lb/in}$$

$$N_{xy} = 382 \text{ lb/in}$$

$$f_c = \frac{334}{.16} = 2088 \text{ psi}, \quad f_s = \frac{382}{.16} = 2388 \text{ psi}$$

$$R_c = \frac{2088}{10500} = .20, \quad R_s = \frac{2388}{10500} = .23$$

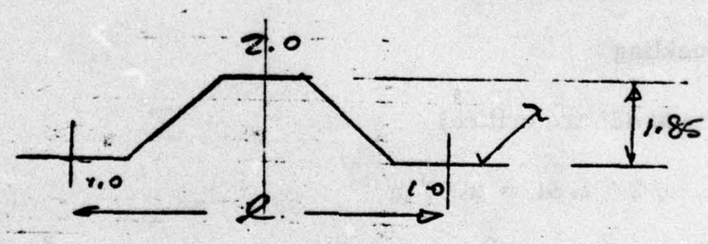
The margin of safety for combined compression and shear is given by

$$\text{M.S.} = \frac{1}{R_c + R_s^2} - 1 = \frac{1}{.20 + .23^2} - 1 = +2.95$$

2.2.3 CONCEPT NO. 3: CORRUGATED WEB ANALYSIS.

Shear Buckling Analysis

The shear buckling analysis for this design is based on the method given in NASA TN D-242



The equivalent flat plate thickness ($\bar{t}$)

$$= \frac{A}{\ell} = \frac{.16(2.0 \times 2 + 1.84 \times 2/\cos 45°)}{2 \times 2 + 2 \times 1.84} = \underline{.192 \text{ in}}$$

Bending stiffness of web

$$= D_1 = \frac{t}{\bar{t}} \frac{Et^3}{12} = \frac{.16 \times 2.9 \times 10^6 \times .16^3}{.192 \times 12} = 824.9 \text{ in lb}$$

Bending stiffness of corrugation

$$= D_2 = F_2 \cdot \bar{t} \cdot \rho^2 \qquad \rho = \text{radius of gyration}$$

$$= 2.9 \times 10^6 \; .192 \times .7476^2 \qquad = \sqrt{\frac{I}{A}} = \sqrt{\frac{.8233}{1.473}} = \underline{.7476 \text{ in}}$$

$$= 311,194 \text{ in lb}$$

$$N_{xy_{cr}} = \frac{4\sqrt[4]{D_1 D_2^{\,3}}}{b^2} \times 8 = \underline{\underline{2351.3 \text{ lb/in}}}$$

$$\tau_{cr} = \frac{N_{x_{cr}}}{t} = \frac{2351.3}{.16} = 14695 \text{ psi}$$

Use cutoff $= \underline{\underline{10500}}$ psi

Applied shear stress $= \dfrac{N_{xy}}{t} = \dfrac{382}{.16} = 2388$ psi

$$\therefore \quad M.S. = \frac{10500}{2388} - 1 = +3.4$$

<u>Compression Buckling Analysis</u>

1. Plate Buckling

The webs at 45° are critical

$$b = \sqrt{2} \cdot 1.84 = 2.60 \text{ in}$$

$$F_{cr} = \frac{K_c \pi^2 F_c}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2 = \frac{4.0 \times \pi^2 \times 2.9 \times 10^6}{12(1-.31^2)} \left(\frac{.16}{2.60}\right)^2$$

$$= \underline{39971 \text{ psi}}$$

Applied stress $= \dfrac{492.2}{t} = \dfrac{492.2}{.192} = 2564$ psi

$$\therefore \quad M.S. \text{ plate buckling} = \frac{10500}{2564 \times 1.5} - 1 = +1.73$$

Column Buckling

Consider a single corrugation (width = 7.7 in)

Applied Load - 492.2 × 7.7 = 3790 lb

The critical column load based on Johnston's second degree parabolic equation is given by

$$F_c = F_c\left[1 - \frac{F_c(1/\rho)^2}{4\pi^2 F_c}\right] = 10500\left[1 - \frac{10500(31/.7476)^2}{4\pi^2 \times 2.9\times 10^6}\right]$$

$$= \underline{8844 \text{ psi}}$$

$$\therefore \quad \text{M.S.} = \frac{8844}{3790 \times 1.5} - 1 = \underline{\underline{+0.56}}$$

2.3 CONCEPT MANUFACTURING COST ANALYSIS

The manufacturing cost analysis performed was intended to show up differences in manufacturing cost among the bridge concepts analyzed. Since this analysis was not intended to predict actual total dollar costs of the bridge sections, features that were common to all concepts were not considered in the analysis.

2.3.1 GROUNDRULES AND ASSUMPTIONS. The following groundrules and assumptions were established for this cost analysis:

1. Production bridge sections were assumed to be 7 meters in length.
2. Steel tension fittings, end bulkheads, fasteners, lower panels, precured G/E tension caps, and upper deck extrusion were assumed identical for all concepts and thus eliminated from the estimates.
3. Total production run assumed was 1000 units produced over 5 years (1980-1985). Assume rate tooling was not required to meet production schedule.
4. All costs were expressed in 1976 dollars and at 1976 prices unless otherwise stated.
5. The factory labor rate was assumed to be $25/hour.
6. The average cost assumed for large quantities of Kevlar/epoxy cloth prepreg in the 1980-1985 time period was $6/pound.

7. An 85% learning rate was assumed.

2.3.2 CONCEPT NO. 1 MANUFACTURING COSTS. The manufacturing sequence and flow chart for Concept No. 1 substructure is presented in Figure 2-7. The shear panels, preformed beads, and buildup are all laid up using a basic 2-ply Kevlar/epoxy cloth module with filaments aligned at ±45-degrees. The 2-ply modules and preformed beads will be transferred to a curing tool in a predetermined sequence with precured pretrimmed G/E lower caps. This assembly will be cured under vacuum, heat and external autoclave pressures.

The shear panel assembly will then be assembled with the lower panel and the extruded aluminum upper deck.

2.3.2.1 Tooling Costs. The tools required to fabricate Concept No. 1 substructure are listed in Table 2-2 with their estimated costs. The total tooling costs for this concept is $104,567 or $105/unit for 1000 units.

2.3.2.2 Raw Material Costs. Raw material costs for Concept No. 1 substructure are listed in Table 2-3. Kevlar/epoxy cloth is the only material required to build the shear panels for this concept. A material usage factor of 1.80 was used in estimating the required quantities of composite prepreg

2.3.2.3 Fabrication Labor Costs. The estimated fabrication labor hours for Concept No. 1 are broken down as follows:

Task	Manhours
1. Layup flat panel modules	
40-inch × 270-inch × 4-ply layup	24
Precompact	12
Cut 65 slots 2-inch × 25 inches	7
Total per module	43
Total × 8 modules	344
2. Layup bead module	
27-inch × 195-inch × 8-ply layup	24
Blank out bead flat patterns	13
Preform beads	16
Total per panel	53
Total × 4 panels	212
3. Layup edge buildups	
a. Outside edge buildups	
66-inch × 270-inch × 2-ply layup	20
Precompact	2
Cut into 12 strips	2.5

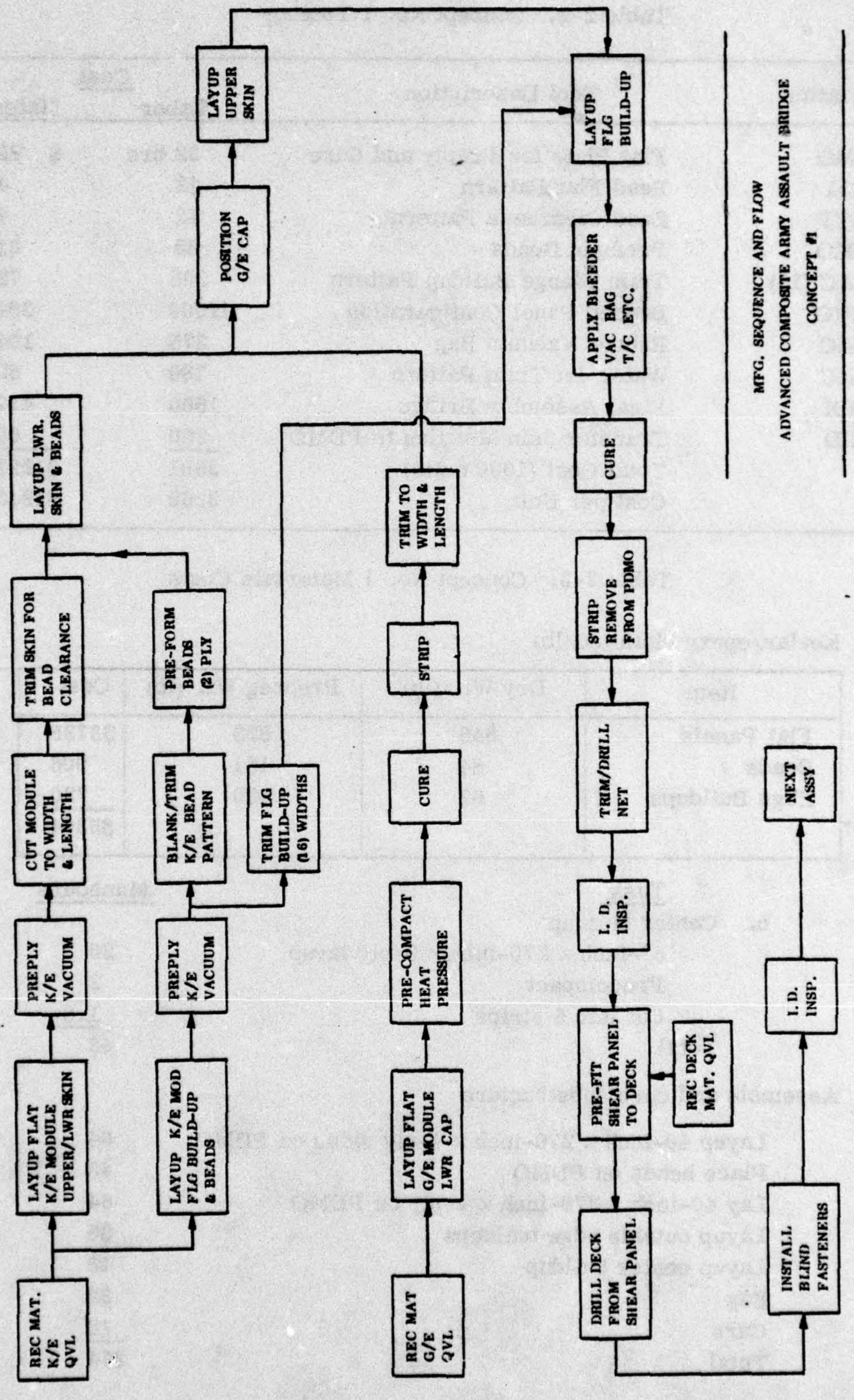


Figure 2-7. Manufacturing Sequence and Flow - Concept No. 1 (Beaded Panel)

Table 2-2. Concept No. 1 Tooling

Abbreviation	Tool Description	Cost Labor	Cost Material
PDMO	Flat Plate for Preply and Cure	32 hrs	$ 890
DKD1	Bead Flat Pattern	12	44
MKTP	Bead Clearnace Pattern	12	44
PDMO	Preform Beads	62	210
TOAC (16)	Trim Flange Buildup Pattern	208	724
PDMO	Beaded Panel Configuration	1000	3942
TOAC	Rubber Vacuum Bag	375	1044
TOAC	Water Jet Trim Pattern	180	522
ASFX	Final Assembly Bridge	1560	4176
MAID	Transfer Skin Modules to PDMO	250	696
	Total Cost (1000 units)	3691	$12292
	Cost per Unit	3.69	$12.3

Table 2-3. Concept No. 1 Materials Costs

Kevlar/epoxy cloth ($6/lb)

Item	Dry Wt. (lb)	Prepreg Wt. (lb)	Cost
Flat Panels	346	623	$3738
Beads	84	151	906
Edge Buildups	67	120	720
			$5364

Task	Manhours
b. Center buildup	
57-inch × 270-inch × 3-ply layup	20
Precompact	2
Cut into 6 strips	1.5
Total	48

4. Assemble and cure substructure

Layup 40-inch × 270-inch × 4-ply skins on PDMO	64
Place beads on PDMO	48
Lay 40-inch × 270-inch × 4-ply on PDMO	64
Layup outside edge buildups	36
Layup center buildup	18
Bag	32
Cure	12
Total	274

Task	Manhours
5. Assemble Substructure to upper deck	
Drill 195 holes	24
Install 195 fasteners	24
Total	48

The total estimated fabrication labor for the prototype shear panel substructure is 926 manhours or $23,150. The average fabrication labor cost per unit for 1000 units is 239 manhours or $5975.

2.3.2.4 Total Manufacturing Costs. The average manufacturing cost for the beaded shear panel substructure, not including upper deck, end bulkheads, lower panel, tension caps and fittings, is itemized as follows:

Tooling	$ 105
Raw Materials	5,364
Fabrication Labor	5,975
Total	$11,444

2.3.3 CONCEPT NO. 2 MANUFACTURING COSTS. The manufacturing sequence and flow chart for Concept No. 2 substructure is presented in Figure 2-8. The Concept No. 2 sandwich consists of upper and lower Kevlar/epoxy cloth facings cocured and bonded to a prespliced, precleaned, and prepotted HRP honeycomb core. The sandwich structure will be prefitted and back drilled through the extruded deck and then mechanically fastened to the deck.

2.3.3.1 Tooling Costs. The tools required to fabricate Concept No. 2 substructure are listed in Table 2-4 with their estimated costs. The total tooling cost for this concept is $90,192 or $90/unit for 1000 units.

2.3.3.2 Raw Material Costs. Raw material costs for Concept No. 2 substructure fabrication are listed in Table 2-5. A Kevlar/epoxy material usage factor of 1.50 was used for this concept since very little trim loss is expected.

2.3.3.3 Fabrication Labor Costs. The estimated fabrication labor hours for Concept No. 2 substructure are broken down as follows:

Task	Manhours
1. Cut buildup strips	
36 pieces 270 inches long × 2-16 inches wide	18

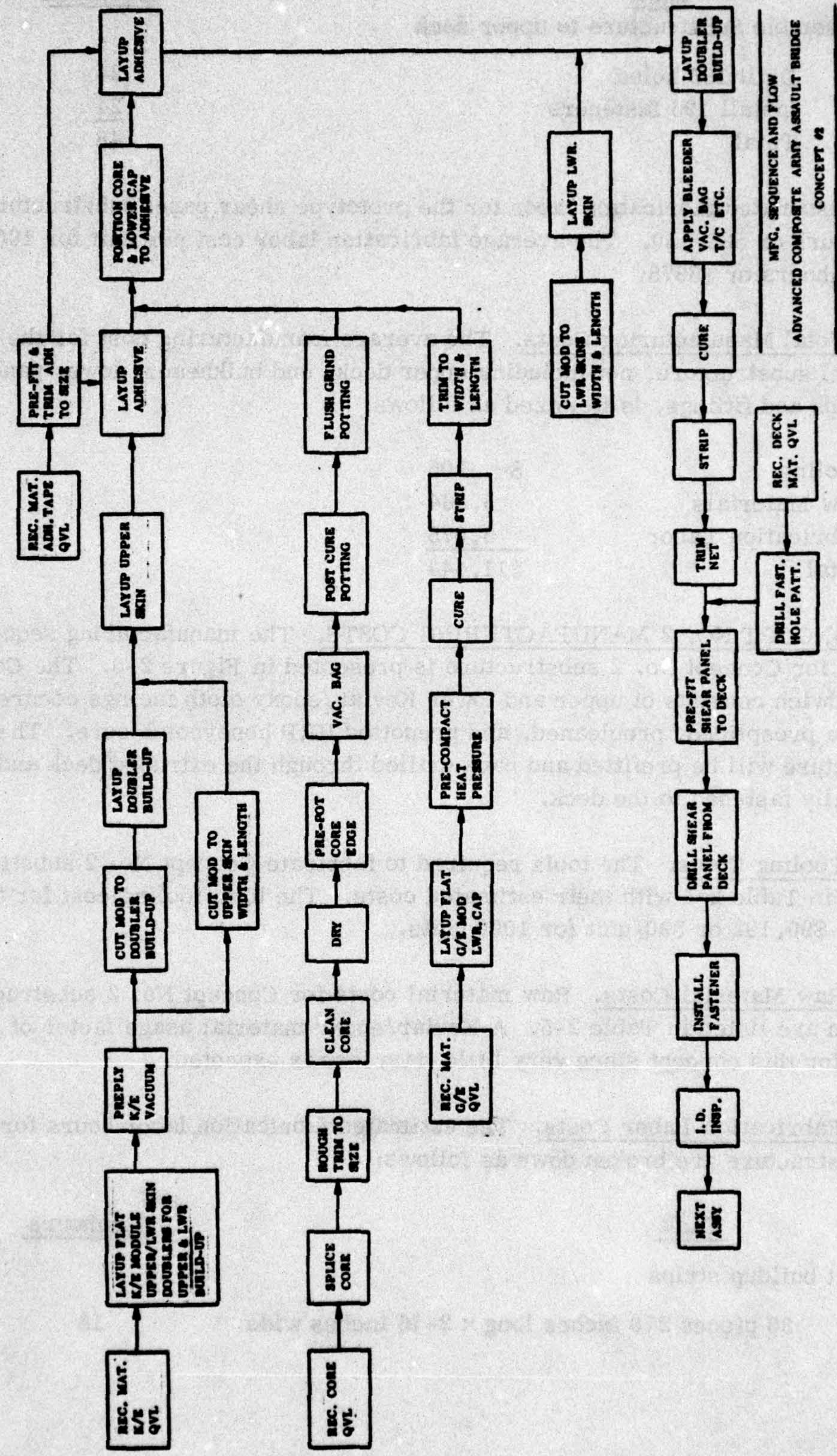


Figure 2.8. Manufacturing Sequence and Flow — Concept No. 2

Table 2-4. Concept No. 2 Tooling Costs

Abbreviation	Tool Description	Cost Labor	Cost Material
PDMO	Flat Plate for Preply	32 hrs	$ 890
PDMO	Upper and Lower Skin	96	250
TOLO	Mylar for Core Perim and Prepot	32	835
PDMO	Final Panel Configuration	800	2245
TRSH	Final Perim Trim	480	1670
DRSH	Deck Attach HL Pattern	180	626
ASFX	Final Assemble Bridge	1560	4176
	Total Cost	3180	$10692
	Cost per Unit	3.18	$10.70

Table 2-5. Concept No. 2 Raw Material Costs

Item	Dry Wt. (lb)	Prepreg Wt. (lb)	Cost($)
1. Kevlar/epoxy cloth ($6/lb)			
Sandwich facings	432	648	$3888
Edge buildups	66	99	594
	498	747	$4482
2. Honeycomb core ($10/sq ft		250 ft^2	2500
3. Potting compound (10/gal)		5 gal	50
4. Adhesive ($3.50/sq ft)		500 ft^2	1750
Total Material Cost			$8782

Task	Manhours
2. Prepare honeycomb	
Trim honeycomb to 34 inches × 264 inches	64
Apply potting compound	80
Clean up potting area	16
Total	160
3. Sandwich assembly	
Place bleeder on PDMO	18
Place 9 buildup strips on PDMO	4.5

Task	Manhours
Lay up skin - 5 ply	60
Lay adhesive on skin	8
Place honeycomb on adhesive	12
Add adhesive to honeycomb	8
Lay skin on adhesive - 5 ply	60
Place 9 buildup strips on skin	4.5
Add bleeder	18
Bag	16
Cure	8
Remove from PDMO	4
Total (one assembly)	221
Total (two assemblies)	442

4. Assemble substructure to upper deck

Drill 260 holes	26
Install 260 fasteners	26
Total	52

The total estimated fabrication labor cost for the prototype sandwich substructure is 672 manhours or $16,800. The average fabrication labor cost per unit for 1000 units is 174 manhours or $4335.

2.3.3.4 Total Manufacturing Costs. The average estimated manufacturing cost per unit for the sandwich substructure, not including upper deck, end bulkheads lower panel, tension caps and fittings is itemized as follows:

Tooling	$ 90
Raw Materials	8,782
Fabrication	4,335
Total	$13,207

2.3.4 CONCEPT NO. 3 MANUFACTURING COSTS. The manufacturing and flow chart for Concept No. 3 substructure is presented in Figure 2.9. The Kevlar/epoxy corrugations will be laminated on a tool capable of producing two shear panels per layup. Four layups and cure cycles will manufacture sufficient corrugations for a complete bridge module. The extruded deck and lower aluminum channels will be predrilled and back drilled into the corrugated panels with the aid of an assembly fixture. The corrugations will be potted locally at the upper and lower edge points.

2.3.4.1 Tooling Costs. The tools required to fabricate Concept No. 3 substructure are listed in Table 2-6 with their estimated costs. The total tooling cost for this concept is $94,158 or $94/unit for 1000 units.

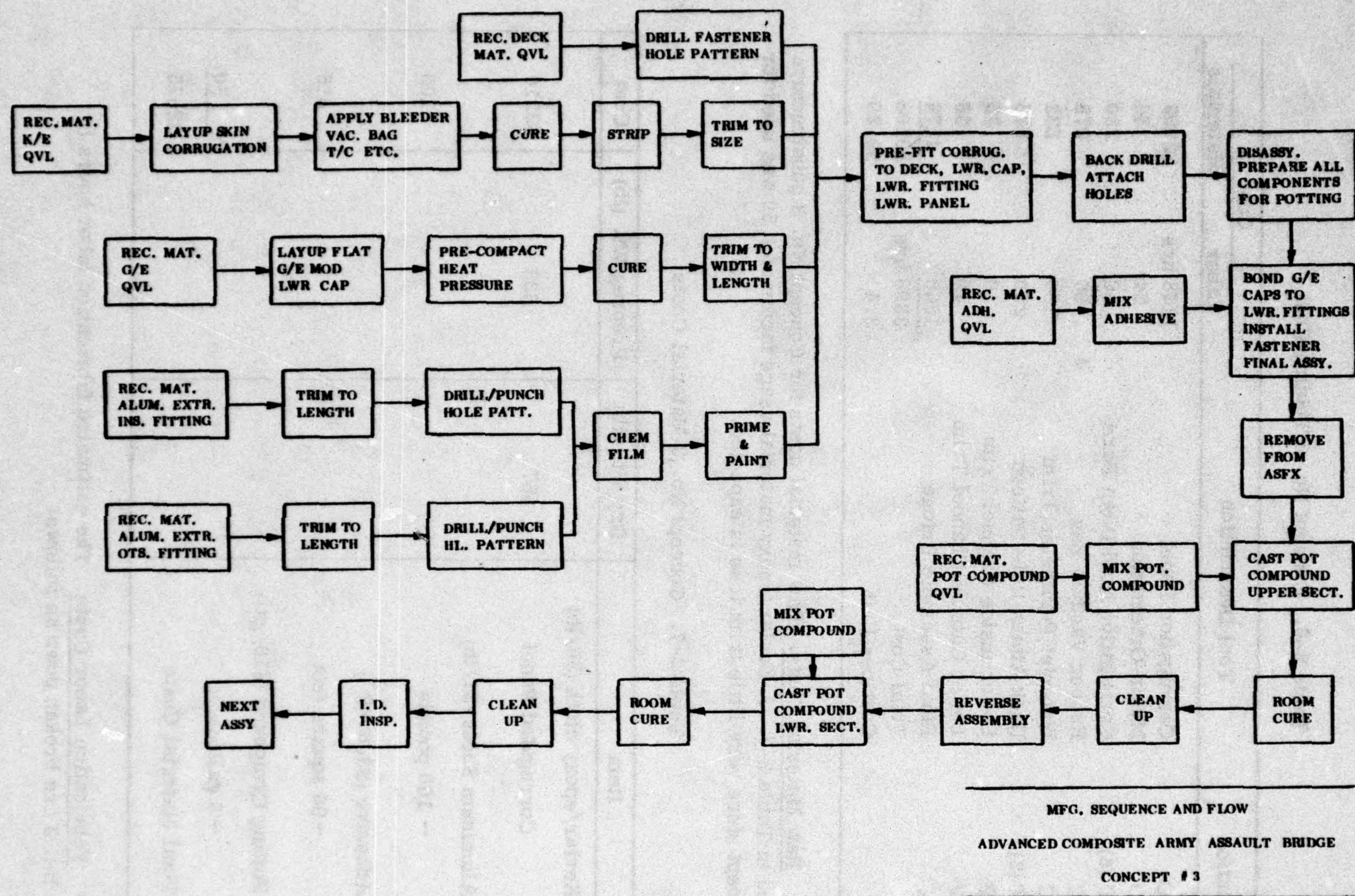


Figure 2.9. Manufacturing Sequence and Flow - Concept No. 3

Table 2-6. Concept No. 3 Tooling Cost

Abbreviation	Tool Description	Cost	
		Labor	Materials
PDMO	Corrugation Panel	1178 hrs	$2993
TOLO	Mylar-Orientation	24	84
TOAC (6)	Corrugation Hold Down Bars	80	250
TOAC	Rubber Vacuum Bag	96	278
TOAC	Waterjet Perimeter Trim	180	522
DRSH (2)	Deck Attach Hole Pattern	260	835
TRTP	Lower Inside Channel Trim	10	35
TRTP	Lower Outside Channel Trim	10	35
ASFX	Final Assemble Bridge	1560	4176
	Total Cost	3398 hrs	$9208
	Cost per Unit	3.4	$9.20

2.3.4.2 Raw Material Costs. Raw material costs for Concept No. 3 substructure are listed in Table 2-7. A Kevlar/epoxy material usage factor of 1.50 was used for this concept since very little trim loss is expected.

Table 2-7. Concept No. 3 Material Costs

Item	Dry Wt. (lb)	Prepreg Wt. (lb)	Cost
1. Kevlar/epoxy cloth ($6/lb)			
Corrugated Panel	357	535	$3210
2. Aluminum Sheet ($1/lb)			
~ 100 pounds			100
3. Adhesive ($3.50/ft^2)			
~90 square feet			315
4. Potting Compound ($10/gal)			
~ 5 gallons			50
Total Material Costs			$3675

2.3.4.3 Fabrication Labor Costs. The estimated fabrication labor hours for Concept No. 3 are broken down as follows:

Task		Manhours
1.	**Layup Corrugated Panels**	
	72-inch × 270-inch × 8-ply layup	96
	Bag	32
	Cure	12
	Total	140
	Total × 2 Panels	280
2.	**Cut 2 Panels in Half**	24
3.	**Fabricate Sheet Metal Channels**	
	Cut sheets 6-inch × 270-inch × .080	8
	Cut sheets 10-inch × 270-inch × .080	8
	Bend-on-brake	24
	Total	40
4.	**Subassemble Panels, Cap and Channels**	
	Fit check in bond tool	16
	Prepare surface for bond	16
	Apply adhesive	12
	Clamp	6
	Total	50
	Total × 2 assemblies	100
5.	**Assemble Substructure to Upper Deck**	
	Place subassemblies in ASFX	24
	Drill 528 holes	55
	Install 528 fasteners	55
	Pot ends of corrugations	100
	Total assemble	234

The total estimated fabrication labor cost for the prototype units is 678 manhours or $16,950. The average labor cost per unit for 1000 units is 175 manhours or $4375.

2.3.4.4 Total Manufacturing Costs. The average manufacturing cost for the corrugated substructure, not including the upper deck, end bulkheads lower panel, tension caps and fittings, is itemized as follows:

Tooling	$ 94
Raw Materials	3675
Fabrication Labor	4375
Total	$8144

2.3.5 COST ANALYSIS SUMMARY. Table 2-8 presents estimated manufacturing cost differences among the three concepts. It must be emphasized that features common to all concepts (i.e., upper deck, tension fittings, etc.) were not included in the cost estimates, thus the figures presented do not reflect total production costs for entire bridge section.

Table 2-8. Concept Cost Summary

Item	Concept No. 1 Beaded Panel	Concept No. 2 Sandwich Panel	Concept No. 3 Corrugated Panel
Tooling			
Materials	13	11	9
Labor	92	79	85
Fabrication			
Materials			
Kevlar/Epoxy	5364	4482	3210
Aluminum	-	-	100
Honeycomb Core	-	2500	-
Adhesive & Potting	-	1800	365
Labor			
Composite Fab	5664	4000	1962
Metal Fab	-	-	258
Assembly	311	335	2155
Total	$11,444	$ 13,207	$ 8,144

The labor cost figures given here represent average unit costs based on prototype labor estimates that have been adjusted to account for learning. The learning rate for hand layup of composite structures is on the order of 85%. At this 85% learning rate, the average fabrication labor cost per unit for 1000 units will be 25.8% of the prototype unit labor cost.

The Kevlar/epoxy material costs shown were calculated using a projected average cost of $6/pound in the 1980-1985 period.

Of the three concepts analyzed, the corrugated substructure (Concept No. 3), in addition to being the lowest cost, appears to offer the greatest potential for future cost reduction through automation of the corrugated panel layup.

2.4 RELIABILITY

The objective of the reliability assessment portion of the conceptual design study was to evaluate the reliability, maintainability, and human factors engineering aspects of the concepts considered.

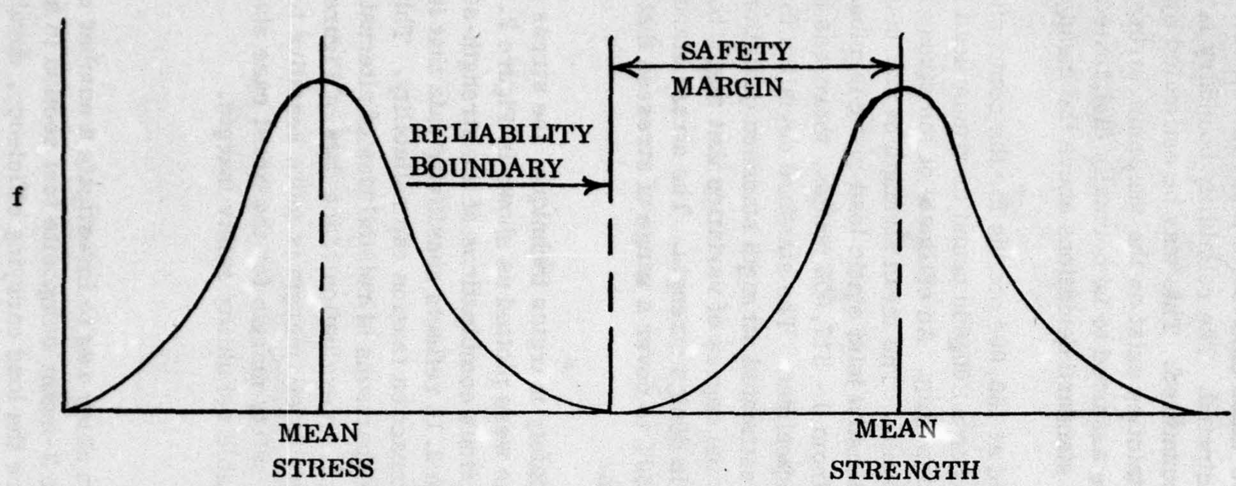
The reliability design concept tradeoffs included consideration of such items as design simplicity, inspectability and estimates of reliability safety margins as an index of concept design reliability. The reliability analysis also used the approach proposed by Lusser for stress-strength relationships as shown in Figure 2.10. Basically the reliability safety margin expresses how much separation there is between the average strength and the maximum stress anticipated. The reliability boundary is defined as the maximum stress which will be encountered. This may be estimated by worst case analysis. In those cases where uncertainties exist on the maximum stresses that may be imposed and where the stresses are assumed to be normally distributed, the reliability boundaries are set at six stress standard deviations above the mean stress.

A value of mean stress was established at 155,000 pounds for the composite lower tension cap specimen. This was based on a 200,000 pound maximum load for a sixty ton tank crossing the seventy-foot bridge span. An estimate of the stress standard deviation was established at 15,000 pounds. The mean strength of 525,000 pounds was based on the results of the lower cap tension joint static load test described in paragraph 3.2.1.4 where, during loading from 0 - 517,000 pounds, there was no indication of failure or impending failure of the specimen. The standard deviation for strength was estimated to be 40,000 pounds. This estimated strength standard deviation was increased and decreased by 50% to determine the degree of variation that might be expected as a function of battle damage or change in design strength. The stress standard deviation was also increased and decreased by 50% to cover a range of stresses that may be a function of severe operating conditions.

Utilizing Lussers reliability through safety margins technique, the stress and strength mean and standard deviation variations were plotted as shown in Figure 2.11 to determine reliability safety margins for various combinations of the strength-stress distributions developed above. Figure 2.11 reflects sensitivity data that indicates which parameters have the greatest impact on tension cap reliability. This approach permits disciplined and systematic comparisons of reliabilities of alternate structural design when sufficient test data exists. An evaluation of the data of Figure 2.11 indicates that the tension cap reliability safety margin is more sensitive to variations in strength than in stress and that the safety margin for the worst case standard deviation is above the minimum allowable reliability safety margin.

2.5 CONCEPT SELECTION

The objective of the Conceptual Design Study was to investigate a number of design concepts and material systems for the 3-meter composite test section in an attempt to reduce production costs and improve the load carrying efficiency, durability and reliability of the component. Three candidate design concepts were generated and subjected to structural, mass properties, and cost analyses. Table 2-10 summarizes the cost and weight differences for the three concepts.



- RELIABILTY BOUNDARY SET AT +6 STRESS STANDARD DEVIATIONS (TYPICAL WHEN UNCERTAINTIES EXIST ON STRESSES THAT MAY BE IMPOSED
- CRITICAL STRESS & STRENGTH RELIABILITY PARAMETERS VARIED TO DETERMINE SENSITIVITY OF RELIABILITY SAFETY MARGINS TO UNCERTAINTIES IN ESTIMATES OF STANDARD DEVIATIONS
- APPROACH PERMITS DISCIPLINED & SYSTEMATIC COMPARISONS OF RELIABILITIES OF ALTERNATIVE STRUCTURAL DESIGNS

Figure 2.10. Reliability Approach

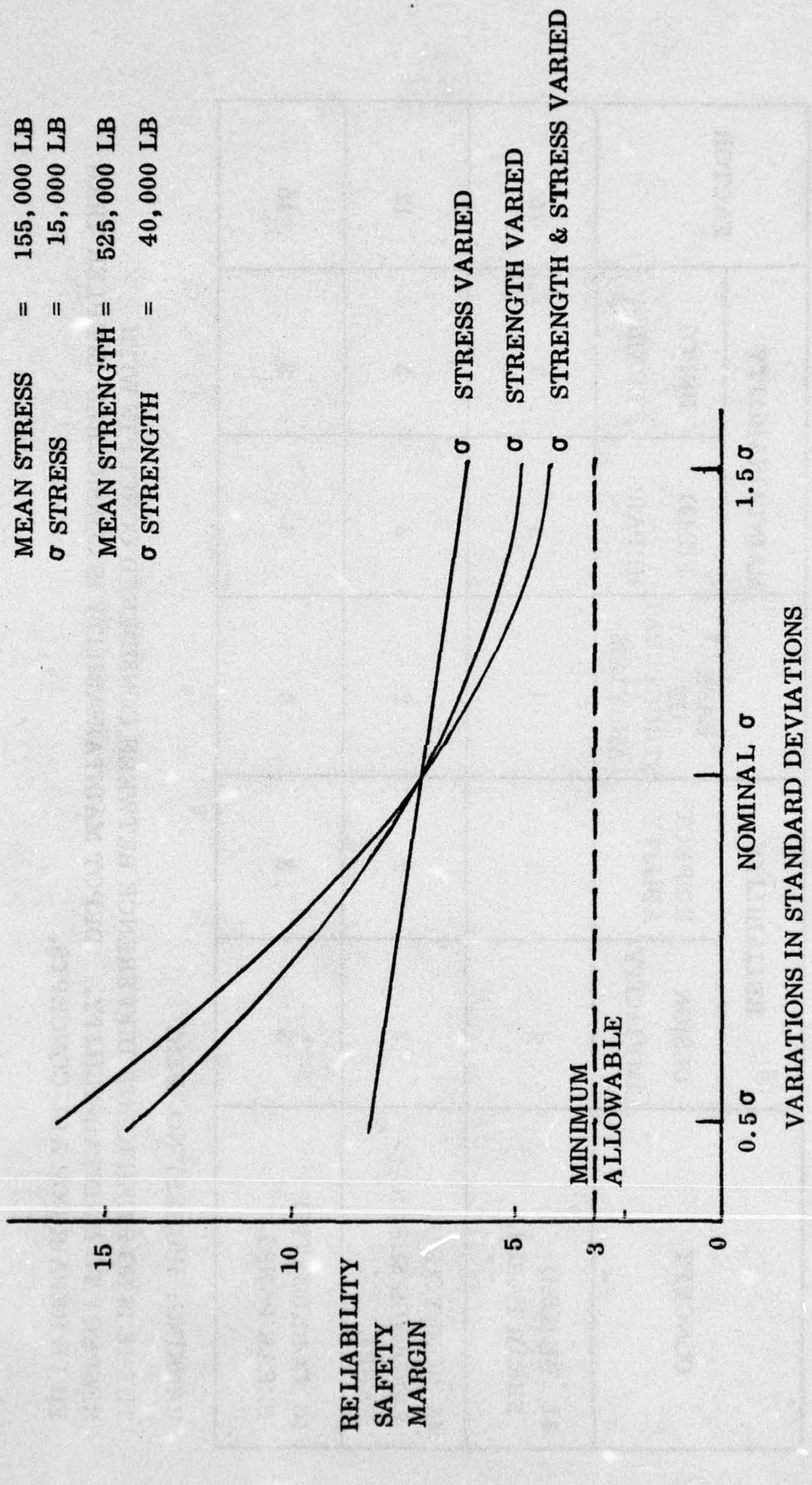


Figure 2.11. Tension Cap Reliability Safety Margins.

Table 2-9. Reliability and Maintainability Factors.

CONCEPT	RELIABILITY			MAINTAINABILITY		FACTOR
	DESIGN SIMPLICITY	INSPECT-ABILITY	EASE OF STRUCTURAL ANAYLSIS	FIELD REPAIR	DEPOT REPAIR	
#1 BEADED SHEAR PANEL	2	1	1	3	3	10
#2 HONEYCOMB SANDWICH SHEAR PANEL	3	2	2	2	3	12
#3 CORRUGATED SHEAR PANEL	3	3	3	3	3	15

RANKING: HIGHEST NO. BEST

THERE IS NO SIGNIFICANT DIFFERENCE BETWEEN CONSIDERED CONCEPTS WITH RESPECT TO MAINTAINABILITY. DEPOT MAINTAINABILITY IS CONSIDERED SIMPLER THAN FIELD REPAIR FOR ALL CONCEPTS.

Table 2-10. Comparison of CTS Design Concepts

Concept	Concept #1	Concept #2	Concept #3
Nomenclature	Beaded Web	Sandwich Web	Corrugated Web
Δ Weight (kg/m)	0	+13.58	+6.43
Δ Cost ($)	0	+1763	-3300

Following the Conceptual Design Study, Concept #3 was selected for application to the composite test section. In addition to providing the lowest production cost, the corrugated web concept is believed to be the lowest risk approach for the CTS design. Concept #3 shear webs are believed more reliable than the other concepts studied due to their simplicity and greater inspectability.

3

DEVELOPMENT TESTING

Following the concept study, a series of subelement and full scale subcomponent test articles were designed, fabricated and tested. The purpose of this testing was to aid in the design and analysis of critical portions of the bridge test section and demonstrate the ability of advanced composite materials to carry the types of internal loads developed at the mid-span of an AVLB, while showing significant weight savings over an all aluminum design.

3.1 SUBELEMENT TESTING

The subelement testing conducted in support of the composite test section design fell into two broad categories; laminate property testing and joint testing. For the laminate property testing, five 0.20-inch thick graphite/epoxy flat panels were made with various ply orientations and then cut into test coupons.

The panel laminates, shown in Table 3-1, contain varying percentages of 0-degree and ±45-degree plies so that design curves could be generated that would be useful for any $[0_n/\pm45_m]$ laminate. Five types of test coupons were cut from each panel:

Type I	1/4-in. Dia. Bolt Bearing Specimen
Type II	1/2-in. Dia. Bolt Bearing Specimen
Type III	Tensile Specimen
Type IV	Tensile Specimen with 1/4-in. Hole
Type V	Multiple Fastener Bolted Specimen

Joint testing was conducted on two configurations of graphite/epoxy specimens with titanium interleaves molded into the laminates at the end joints. These specimens were designated Type VI and Type VII specimens.

Table 3-1. G/E Test Panel Laminates

Panel I. D.	Laminate	Percent (0)	Material
ABB-20	$[\pm45/0/\pm45]_{2s}$	20	T-300/934 G/E
ABB-40	$[0/\pm45/0/\pm45/0/\pm45/0]_s$	40	↑
ABB-60	$[0_3/\pm45]_{2s}$	60	
ABB-80	$[0_4/\pm45/0_4]_s$	80	↓
ABB-0	$[\pm45]_{5s}$	0	T-300/934 G/E

3.1.1 <u>TYPE I SPECIMEN TESTING</u>. The Type I subelement specimen testing was performed to determine the ultimate bearing strength and residual bearing strength after 15,000 fatigue cycles of the various laminates presented in Table 3-1.

The Type I specimen configuration is illustrated in Figure 3.1. Four Type I specimens were cut from each of the five panels listed in Table 3-1. Two specimens from each panel were statically loaded to failure in tension and the remaining two were fatigue cycled and then failed in tension.

Testing was conducted in a universal test machine using a setup similar to that shown in Figure 3.2. Typical load-deflection curves for the static testing are presented in Figure 3.3. As can be seen from these curves, most of the specimens suffered an initial failure and then proceeded to pick up more load prior to final fracture.

The load at the initial failure is considered to be the ultimate static strength of the specimen. Following the static testing, fatigue tests were run on two specimens from each laminate. The fatigue testing consisted of 15,000 load cycles from a minimum of 2.8% to a maximum of 56% of the ultimate static strength for each laminate. Load-deflection curves for residual strength testing of the fatigue cycled specimens are presented in Figure 3.4. Results of all Type I specimen testing are presented in Table 3-2 and in graphical form in Figure 3.5. Figure 3.6 illustrates the Type I specimen failure modes experienced for the five different laminates tested.

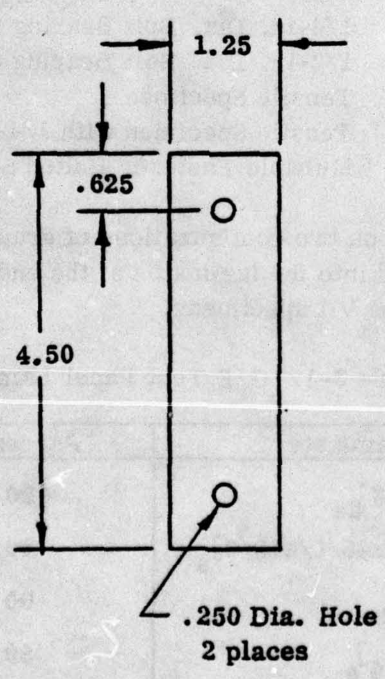


Figure 3-1. Type I Specimen Configuration

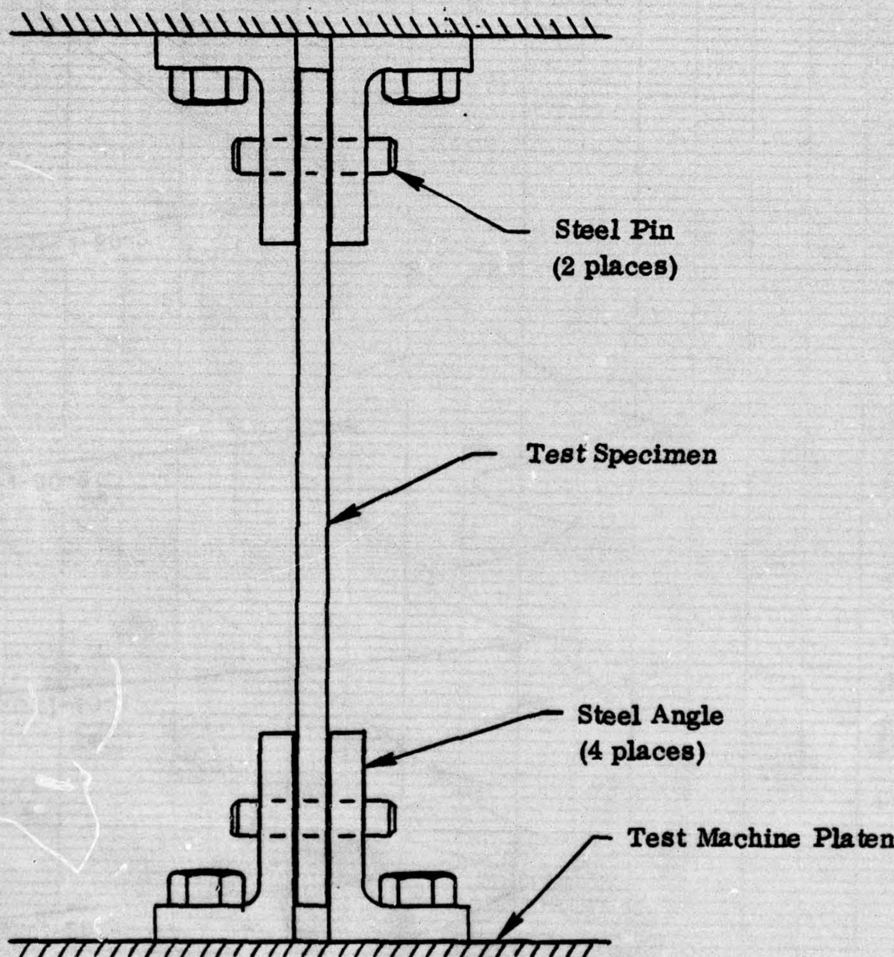


Figure 3.2. Pin-Clevis Test Setup

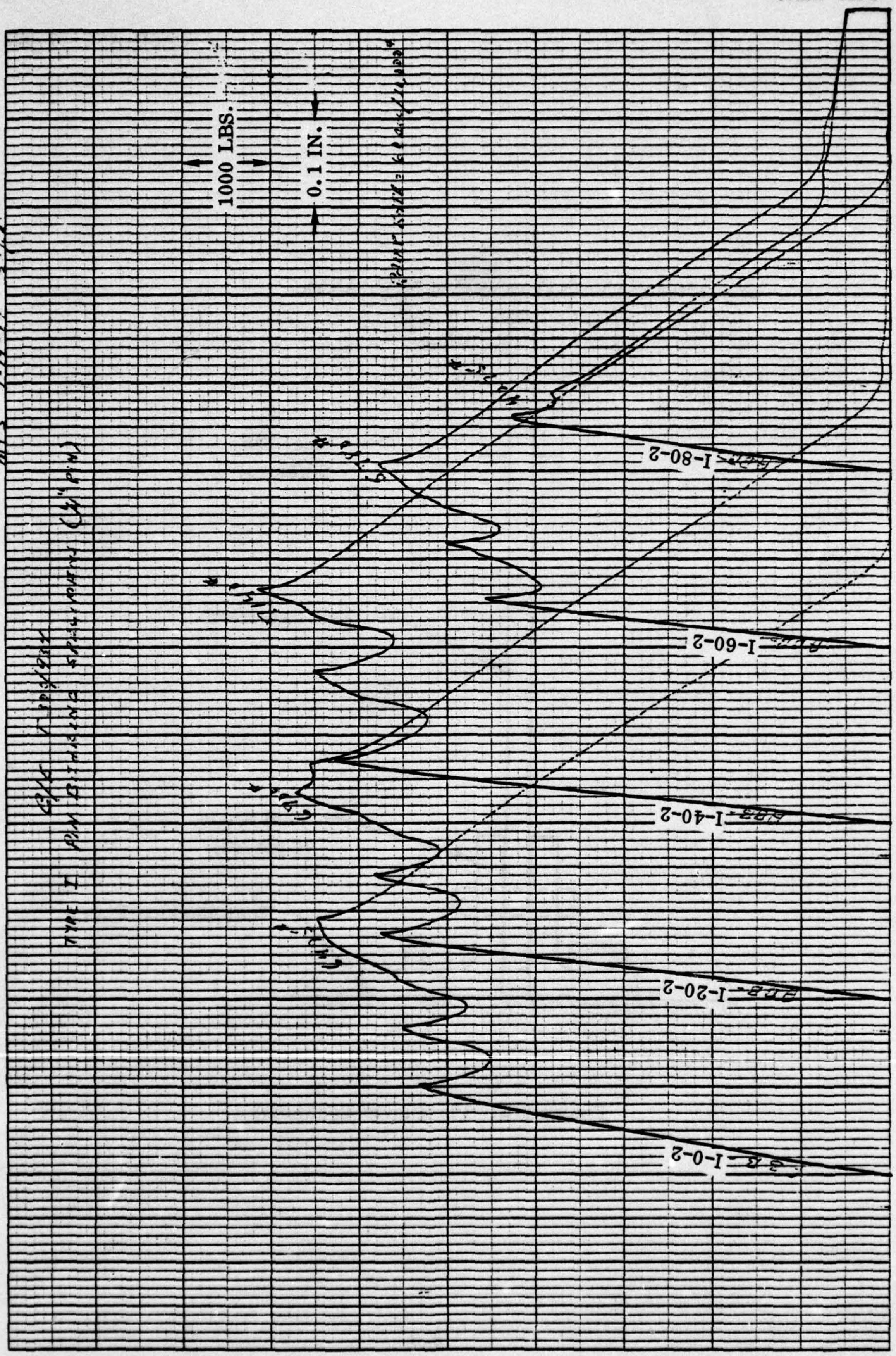
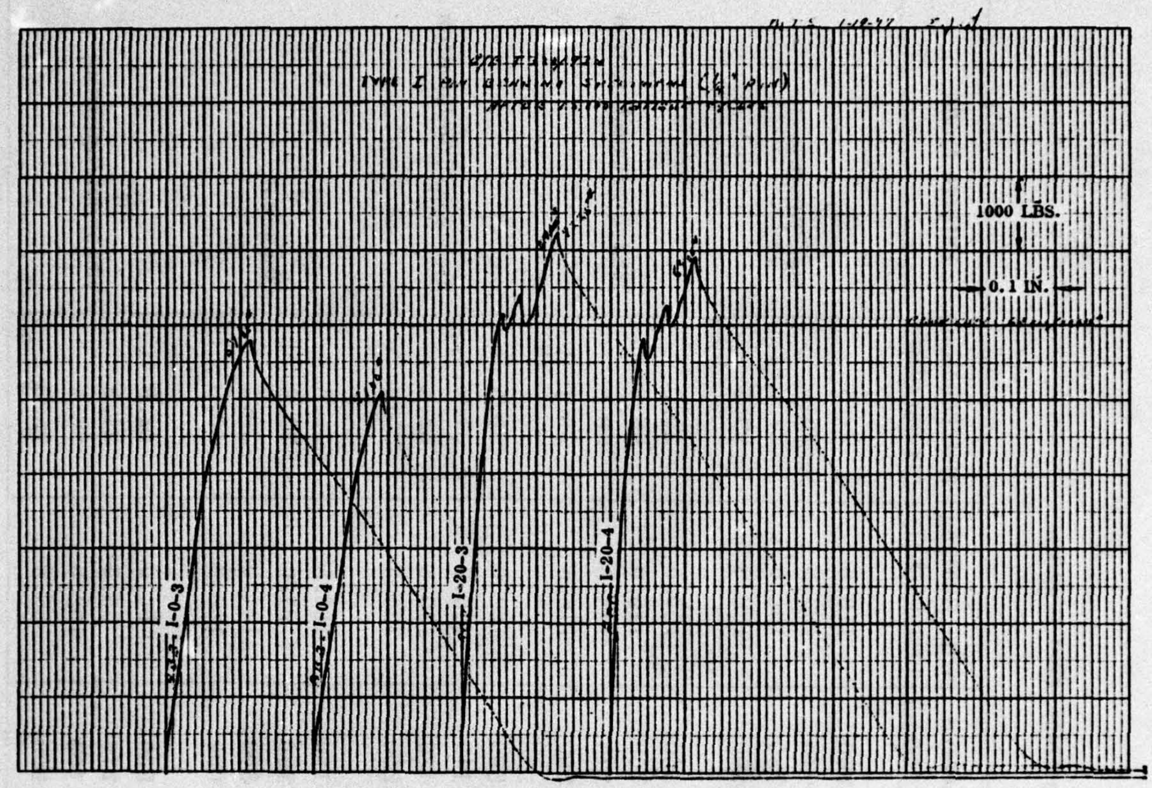


Figure 3.3. Typical Static Load-Deflection Curves - Type I Specimens



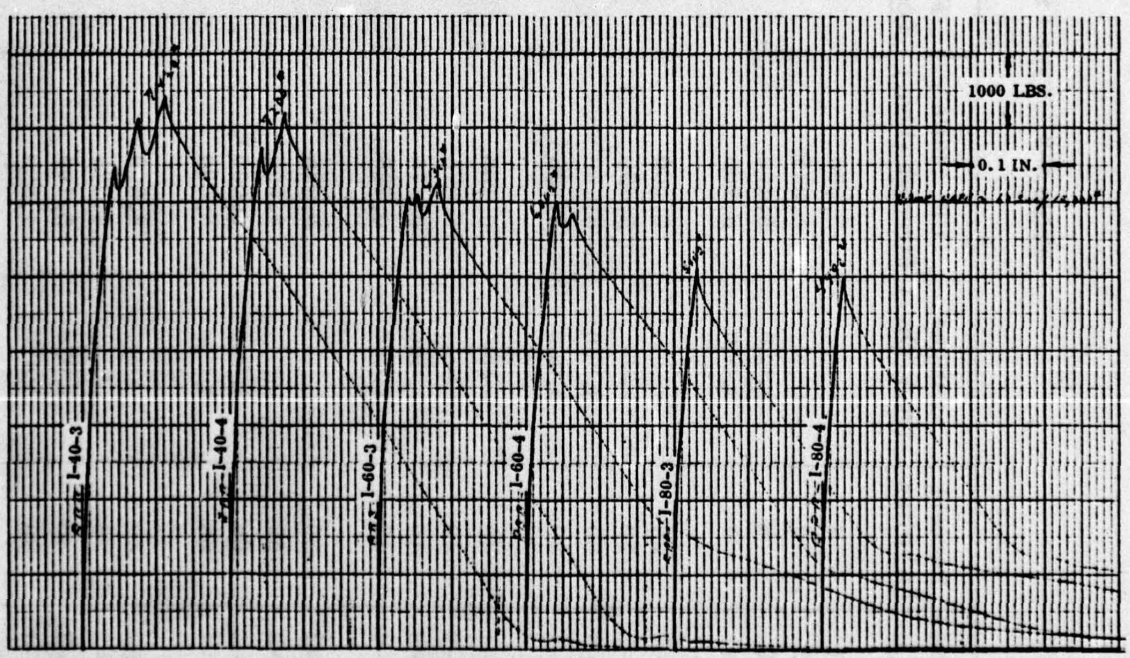


Figure 3.4. Residual Strength Load-Deflection Curves - Type I Specimens

Table 3-2. Type I Specimen Test Results

Specimen No.	Percent [0] Plies	Fatigue Load (Lbs.)	Ult. Static Strength (Lbs.)	Fracture Load (Lbs.)	Ult. Bearing Stress (KSI)	Net Tension Stress (KSI)	Failure Mode
I-0-1	0	----	5,500	6,350	110.0	27.5	
I-0-2	0	----	5,325	6,475	106.5	26.6	Net Tension
I-0-3	0	3,020	5,400	5,780	108.0	27.0	
I-0-4	0	3,020	5,100	5,100	102.0	25.5	
I-20-1	20	----	6,000	6,850	120.0	30.0	
I-20-2	20	----	5,750	6,700	115.0	28.8	Bearing/Combination
I-20-3	20	3,260	6,150	7,225	123.0	30.8	
I-20-4	20	3,260	5,825	6,900	116.5	29.1	
I-40-1	40	----	6,100	6,500	122.0	30.5	
I-40-2	40	----	6,275	7,140	125.5	31.4	Bearing/Combination
I-40-3	40	3,460	6,475	7,420	129.5	32.4	
I-40-4	40	3,460	6,725	7,200	134.5	33.6	
I-60-1	60	----	5,125	6,100	102.5	25.6	
I-60-2	60	----	4,550	5,780	91.0	22.8	Shearout
I-60-3	60	2,740	6,050	6,300	121.0	30.3	
I-60-4	60	2,740	6,000	6,000	120.0	30.0	
I-80-1	80	----	4,500	4,500	90.0	22.5	
I-80-2	80	----	4,275	4,275	85.5	21.3	Shearout/Splitting
I-80-3	80	2,420	5,100	5,100	102.0	25.5	
I-80-4	80	2,420	4,990	4,990	99.8	25.0	

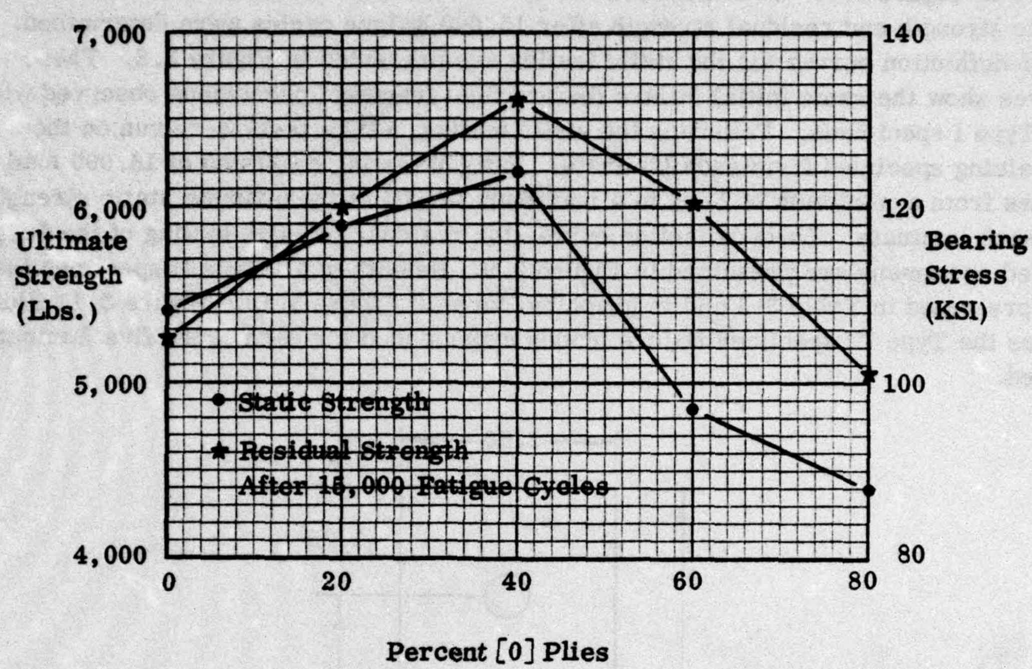


Figure 3.5. Type I Specimen Strength Vs. Percentage of [0] Plies in Laminate

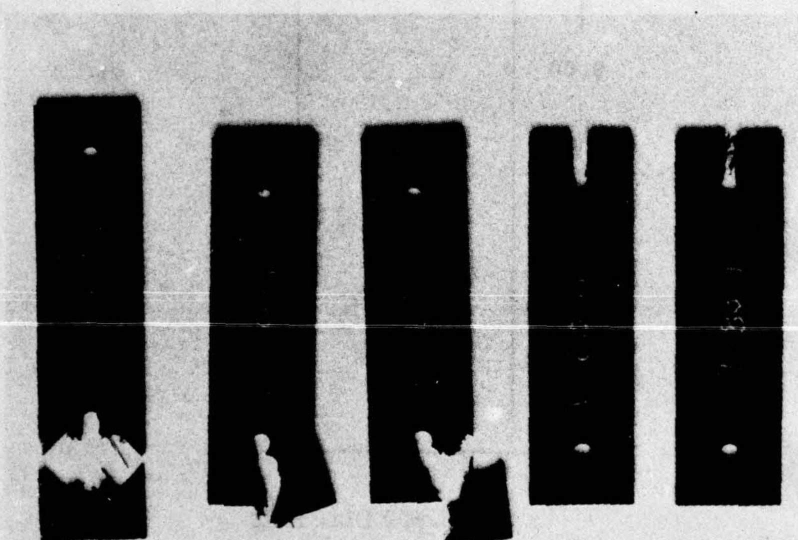


Figure 3.6. Type I Specimen Failure Modes

3.1.2 TYPE II SPECIMEN TESTING. The Type II specimen configuration is shown in Figure 3.7. Two specimens of each of the five laminates were tested. Both static strength and residual strength after 15,000 fatigue cycles were determined. Load-deflection curves for the static testing are presented in Figure 3.8. These curves show the same initial failure (before final fracture) phenomena observed with the Type I specimens. Following the static testing, fatigue tests were run on the remaining specimen from each laminate. Fatigue testing consisted of 15,000 load cycles from a minimum of 2.8% to a maximum of 57% of the ultimate static strength for each laminate. Load-deflection curves for residual strength testing of the fatigue cycled specimens are presented in Figure 3.9. Results of all Type II specimen testing are presented in Table 3-3 and in graphical form in Figure 3.10. Figure 3.11 illustrates the Type IV specimen failure modes experienced for each of the five laminates tested.

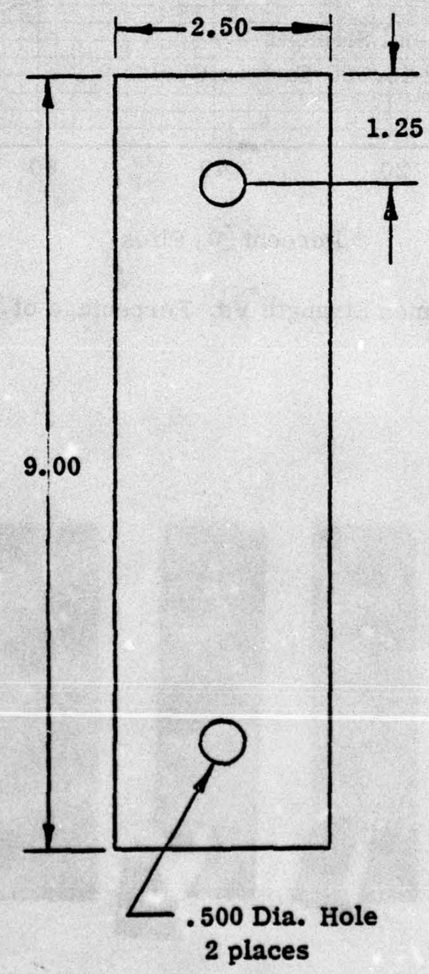


Figure 3.7. Type II Specimen Configuration

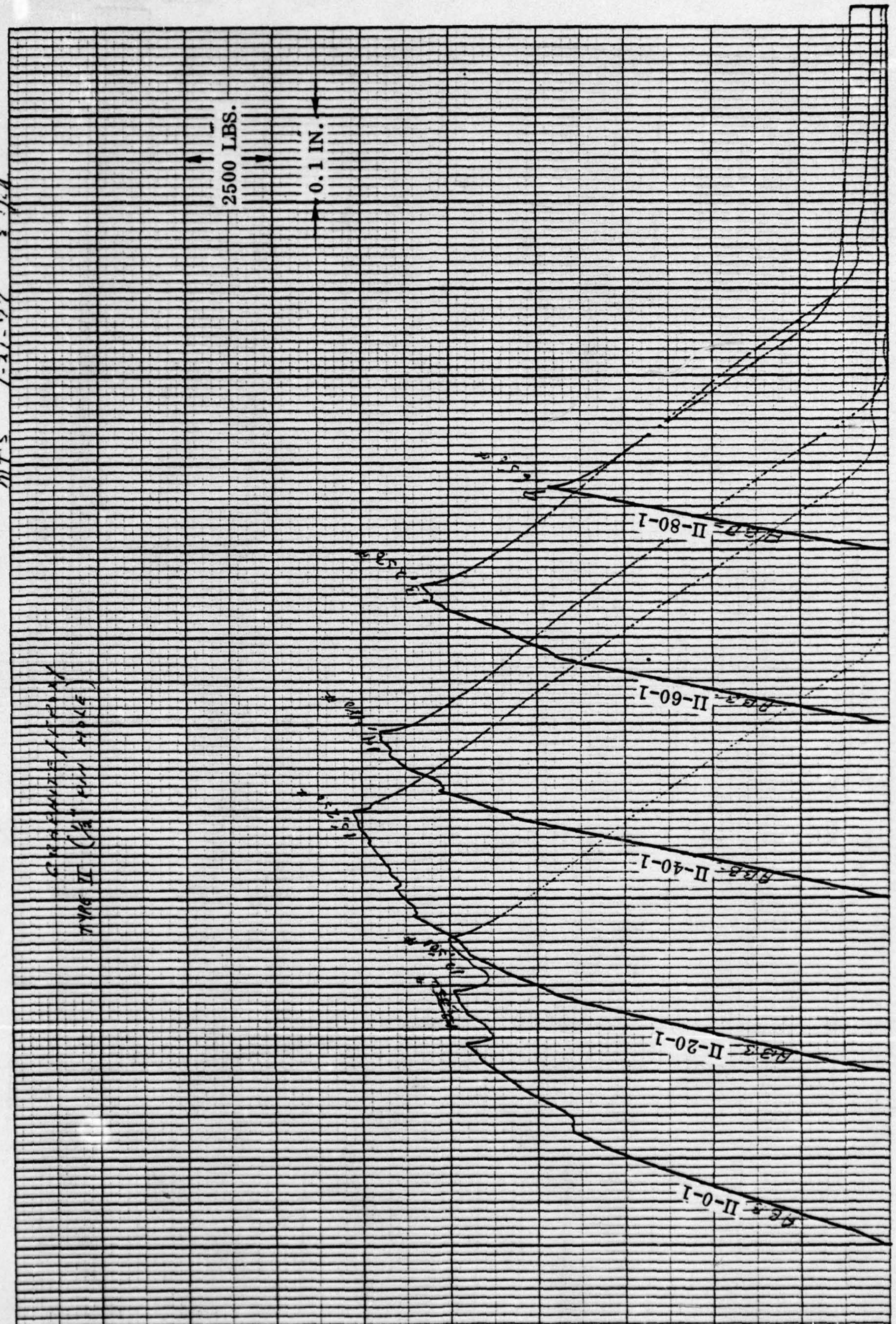


Figure 3.8. Static Load-Deflection Curves for Type II Specimens

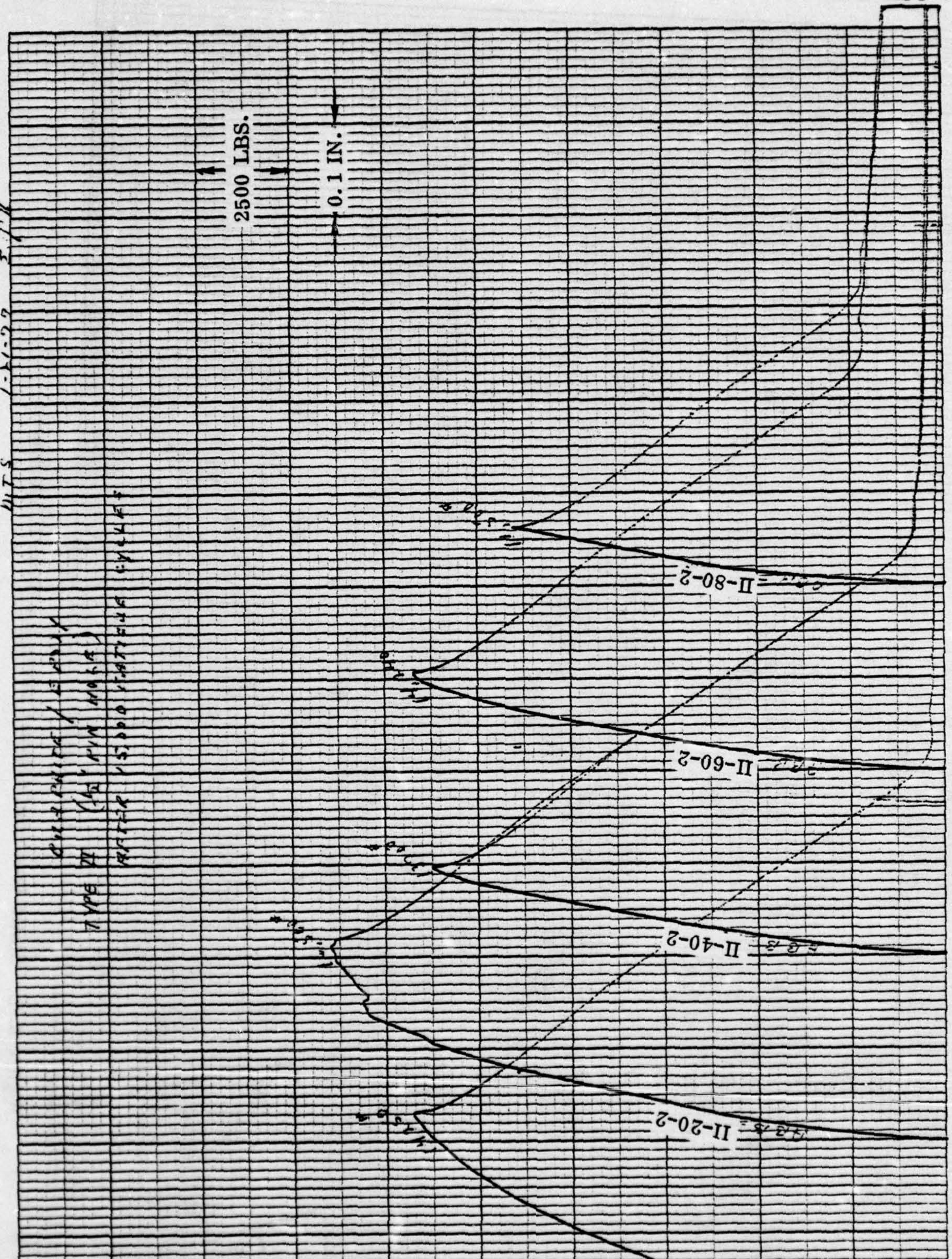


Figure 3.9. Residual Strength Load-Deflection Curves - Type II Specimens

Table 3-3. Type II Specimen Test Results

Specimen No.	Percent [0] Plies	Fatigue Load (Lbs.)	Ult. Static Strength (Lbs.)	Fracture Load (Lbs.)	Ult. Bearing Stress (KSI)	Net Tension Stress (KSI)	Failure Mode
II-0-1	0	----	9,000	12,350	90.0	22.5	Net Tension
II-0-2	0	5,100	13,150	14,250	131.5	32.9	
II-20-1	20	----	9,600	15,250	96.0	24.0	Bearing/Combination
II-20-2	20	5,380	14,000	16,500	140.0	35.0	
II-40-1	40	----	10,150	14,480	101.5	25.4	Bearing/Combination
II-40-2	40	6,080	13,000	13,700	130.0	32.5	
II-60-1	60	----	9,500	13,250	95.0	23.8	Shearout
II-60-2	60	5,380	13,350	14,240	133.5	33.4	
II-80-1	80	----	9,650	9,650	96.5	24.1	Shearout/Splitting
II-80-2	80	5,460	11,500	11,500	115.0	28.8	

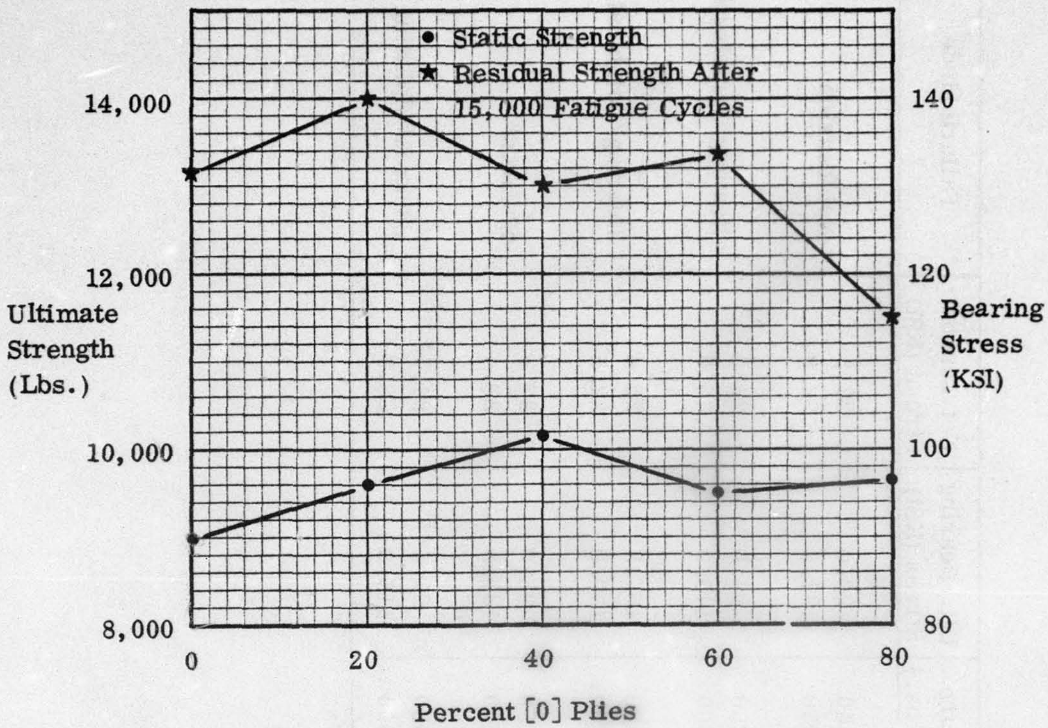


Figure 3.10. Type II Specimen Strength vs. Percentage of [0] Plies in Laminate

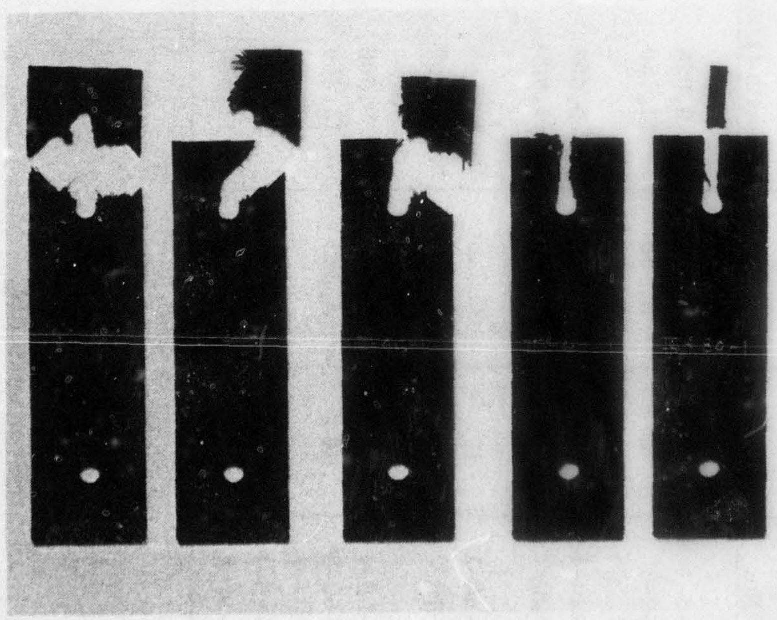


Figure 3.11. Type II Specimen Failure Modes

3.1.3 TYPE III AND IV SPECIMEN TESTING. The Type III and IV specimen configurations are illustrated in Figure 3.12. Type III and IV specimens are identical except for the addition of a 1/4-inch diameter hole drilled through the center of the Type IV specimens. Two specimens of each type were made from each of the panels listed in Table 3-1 and loaded to failure in tension. Results of this testing are listed in Table 3-4 and presented graphically in Figure 3.13. Figures 3.14 and 3.15 illustrate the Type III and IV specimen failure modes experienced for each of the laminates tested.

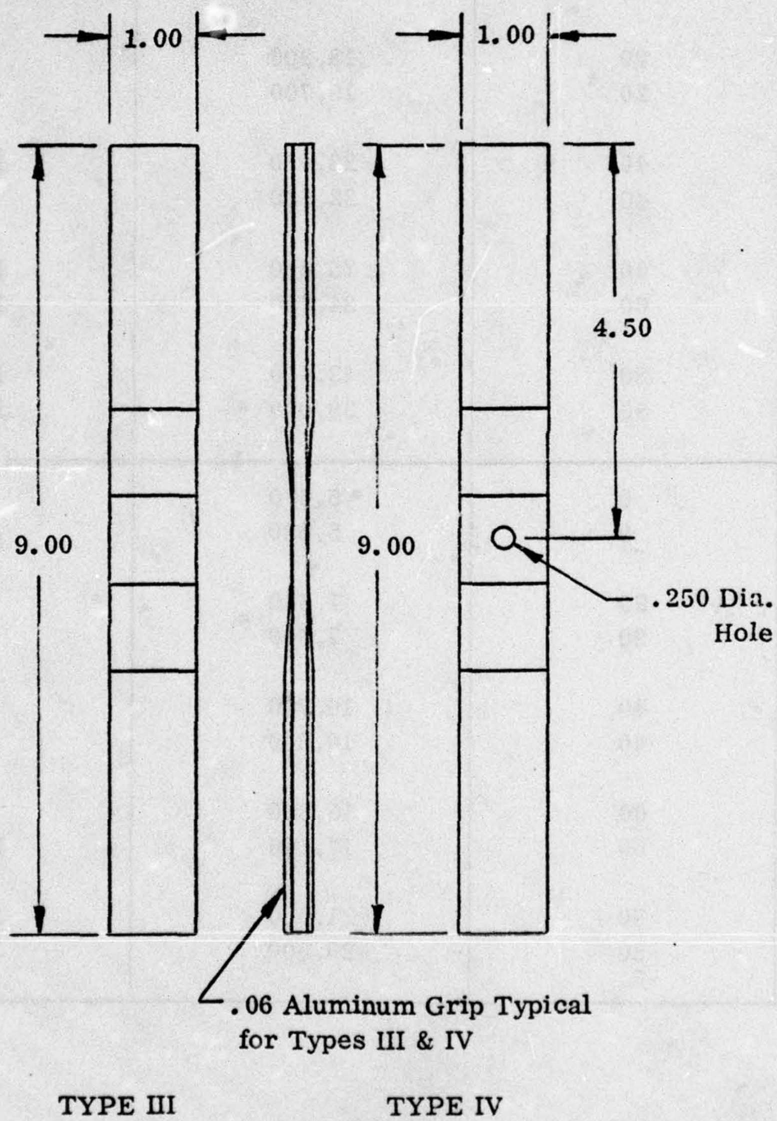


Figure 3.12. Type III and IV Specimen Configurations

Table 3-4. Type III and IV Specimen Test Results

Specimen No.	Percent [0] Plies	Failure Load (Lbs.)	Net Section Stress (KSI)
III-0-1	0	6,740	29.8
III-0-2	0	6,470	28.7
III-20-1	20	13,200	60.9
III-20-2	20	15,700	70.3
III-40-1	40	23,000	101.0
III-40-2	40	22,500	99.6
III-60-1	60	25,800	118.0
III-60-2	60	34,700	155.0
III-80-1	80	43,400	192.0
III-80-2	80	39,000	177.0
IV-0-1	0	5,670	33.3
IV-0-2	0	5,630	32.7
IV-20-1	20	7,680	44.7
IV-20-2	20	7,560	44.1
IV-40-1	40	10,700	63.2
IV-40-2	40	10,600	63.7
IV-60-1	60	15,800	94.0
IV-60-2	60	17,500	104.0
IV-80-1	80	21,000	124.0
IV-80-2	80	20,800	122.0

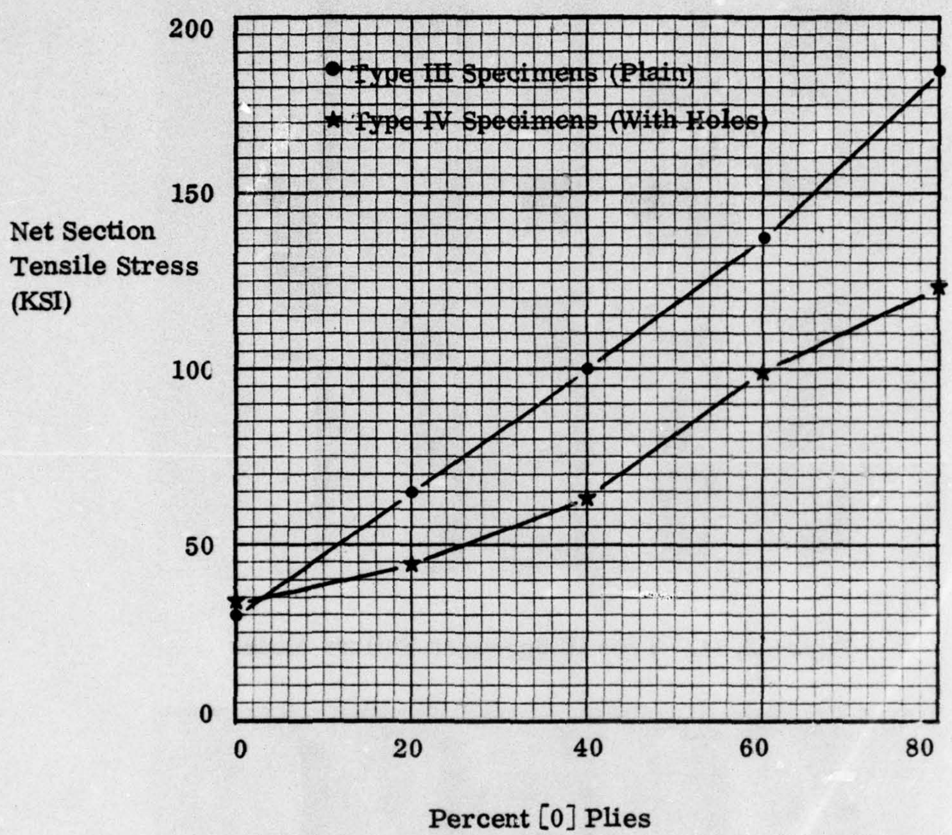


Figure 3.13. Type III & IV Specimen Failure Stress vs. Percentage of [0] Plies in Laminate

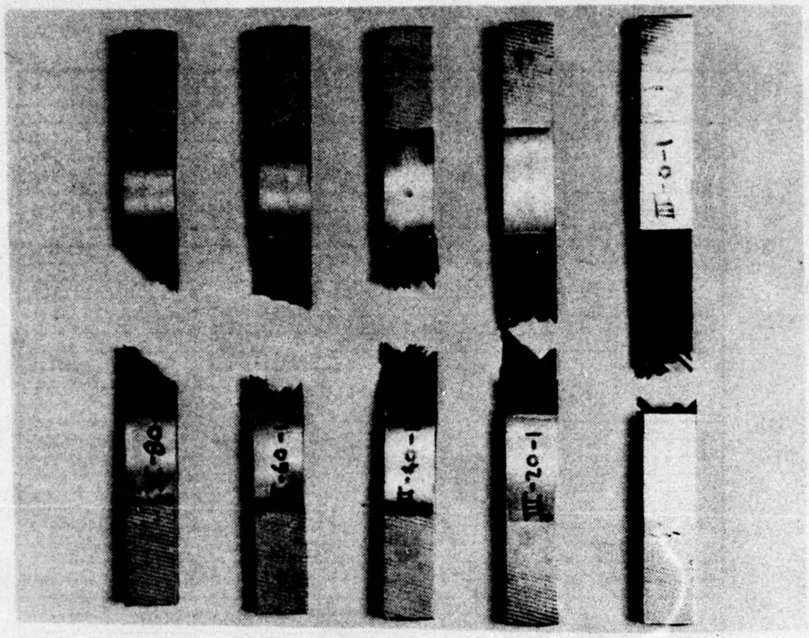


Figure 3.14. Type III Specimen Failure Modes

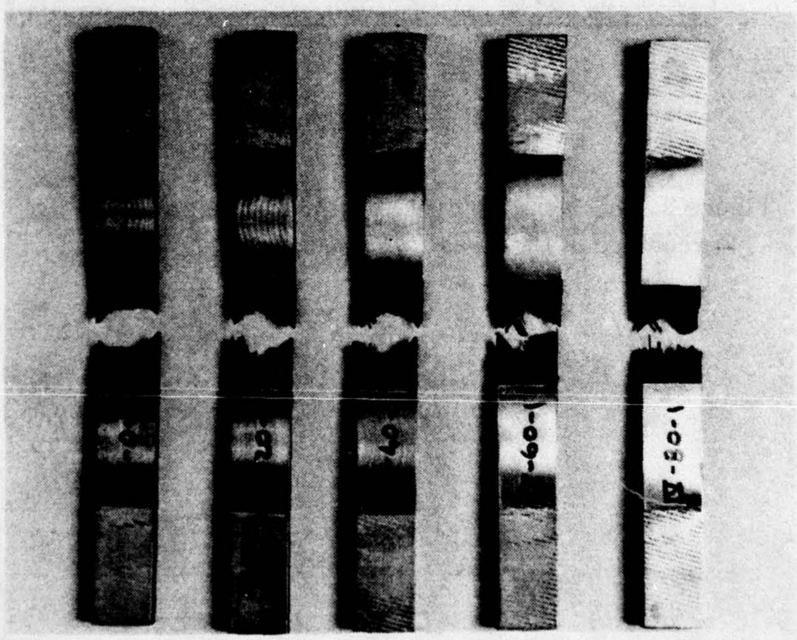


Figure 3.15. Type IV Specimen Failure Modes

3.1.4 TYPE V SPECIMEN TESTING. The Type V specimen configuration is shown in Figure 3.16. The Type V specimens were built from each of the panels listed in Table 3-1. The specimens were simply loaded to failure in tension. Test results for the Type V specimens are listed in Table 3-5 and presented graphically in Figure 3.17. Figure 3.18 illustrates the Type V specimen failure modes experienced for each of the five laminates tested.

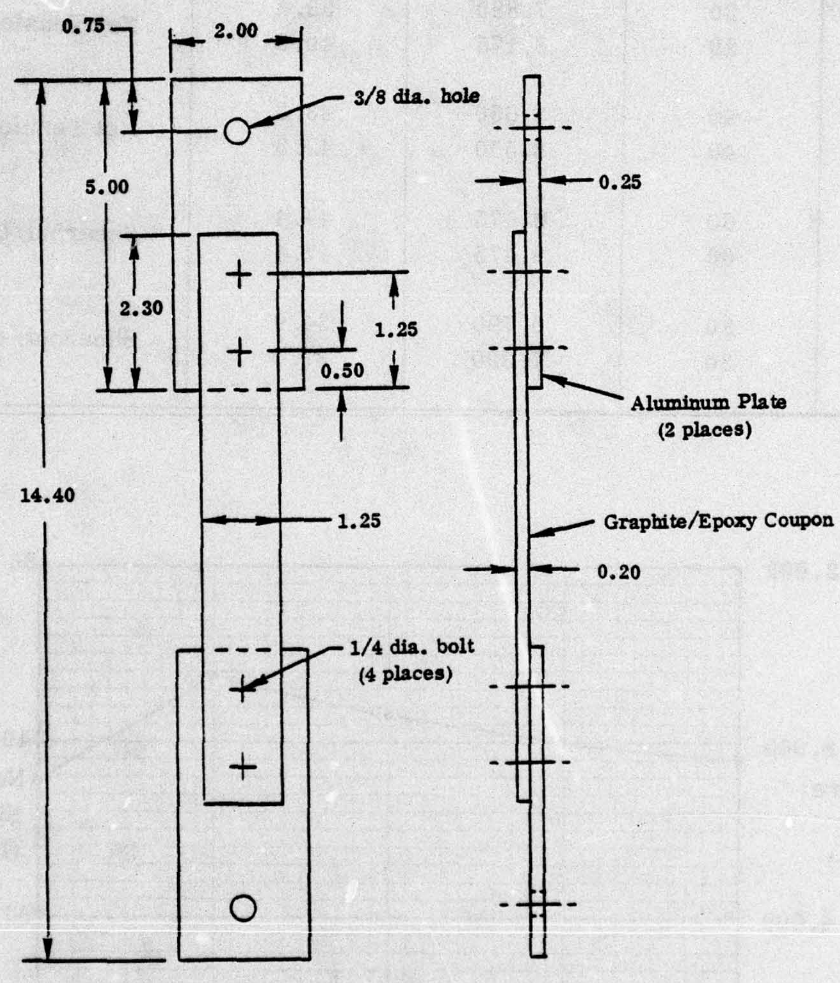


Figure 3.16. Type V Specimen Configuration

Table 3-5. Type V Specimen Test Results

Specimen No.	Percent [0] Plies	Failure Load (Lbs.)	Net Section Stress (KSI)	Failure Mode
V-0-1	0	7,725	38.6	Net Tension
V-0-2	0	7,650	38.3	
V-20-1	20	7,880	39.4	Net Tension
V-20-2	20	8,175	40.9	
V-40-1	40	8,650	43.3	Net Tension
V-40-2	40	8,550	42.8	
V-60-1	60	9,475	47.4	Shearout/Combination
V-60-2	60	9,475	47.4	
V-80-1	80	6,790	34.0	Shearout/ Splitting
V-80-2	80	7,390	37.0	

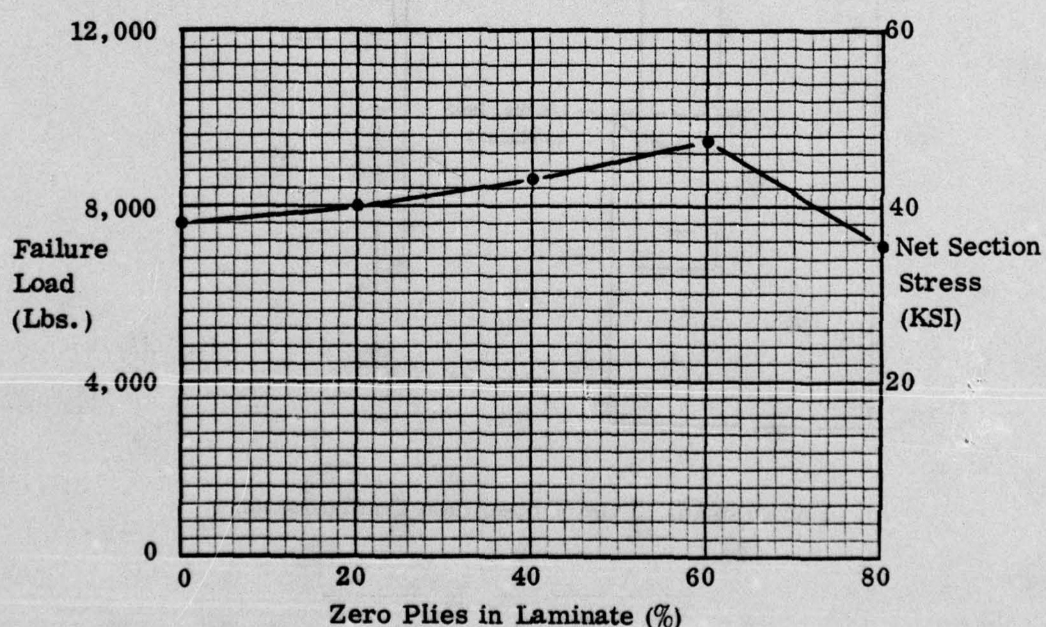


Figure 3.17. Type V Specimen Strength vs. Percentage of [0] Plies in Laminate

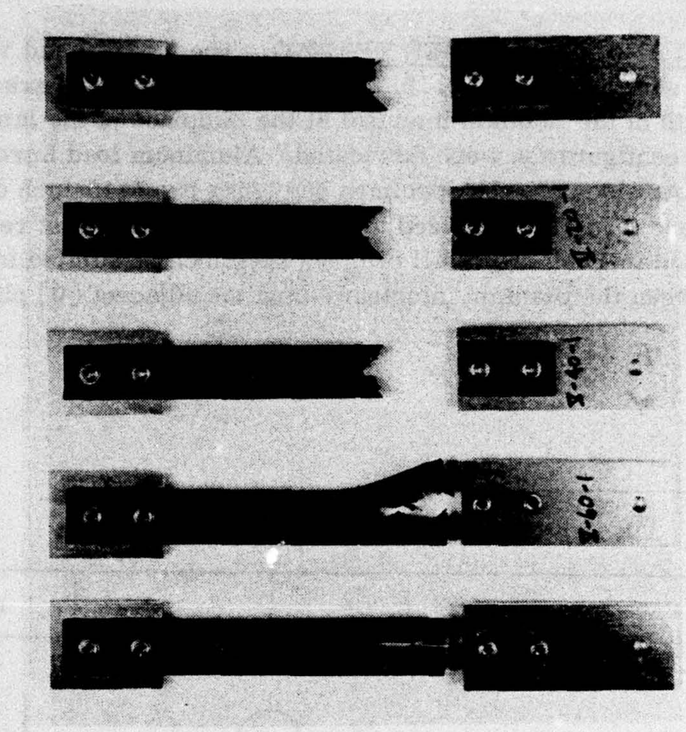
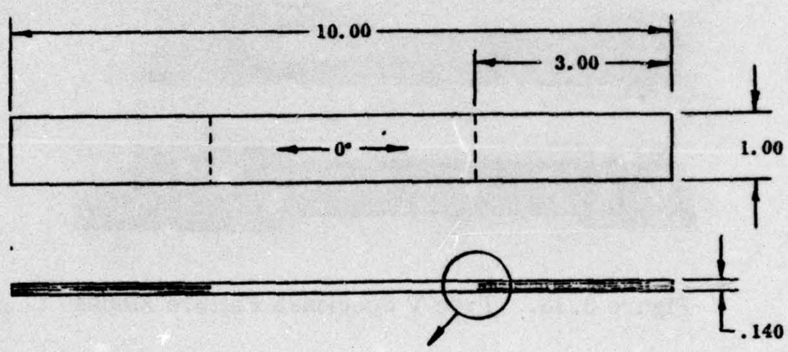


Figure 3.18. Type V Specimen Failure Modes

3.1.5 <u>TYPE VI AND VII SPECIMEN TESTING</u>. The Type VI and VII specimen configurations are shown in Figure 3.19. The two specimen types are identical except for the length of the titanium interleaf at the midplane of the laminates. Five specimens of each configuration were fabricated. Aluminum load introduction plates were fastened to both sides of each specimen end using two 5/16-inch diameter bolts. The assemblies were then simply loaded to failure in tension. Test results for these specimens are listed in Table 3-6. All of these specimens exhibited interlaminar shear failures between the titanium interleaves and the adjacent [0] plies as illustrated in Figure 3.20.



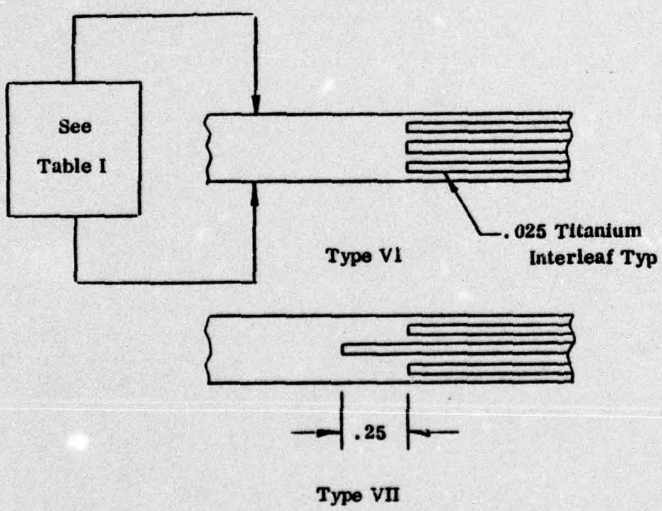


Table I	
Ply No.	Orientation
1	0
2	0
3	45
4	-45
5	0
6	0
7	45
8	-45
9	0
10	0
11	-45
12	45
13	0
14	0

Figure 3.19. Type VI and VII Specimen Configurations

Table 3-6. Type VI and VII Specimen Test Results

Specimen No.	Failure Load (Lbs.)	Tensile Stress (KSI)
VI-1	10,850	79.2
VI-2	10,125	68.9
VI-3	9,025	60.6
VI-4	9,725	65.9
VI-5	11,025	77.4
VII-1	12,300	91.1
VII-2	11,375	77.6
VII-3	11,500	78.4
VII-4	10,900	74.8
VII-5	11,950	84.5

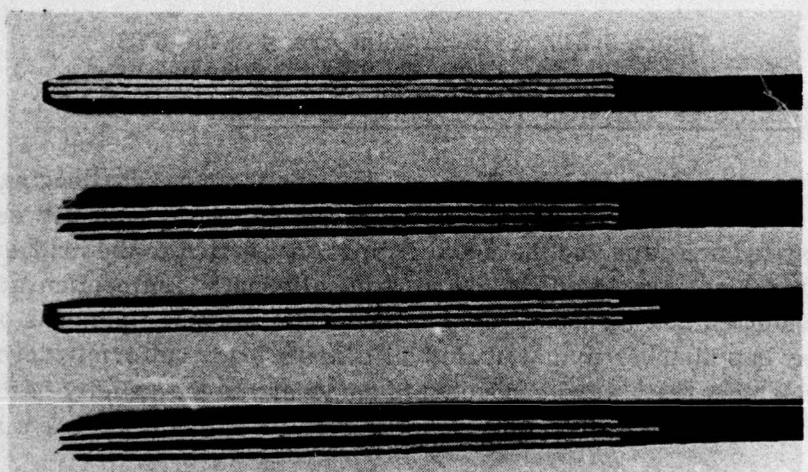


Figure 3.20. Type VI and VII Specimen Failure Mode

3.2 FULL SIZE SUBCOMPONENT TESTING

Two full scale composite test articles representing the critical joint areas of the 3-meter composite test section were designed, fabricated, and tested. The locations of the critical joint areas on the test section are shown in Figure 3.21.

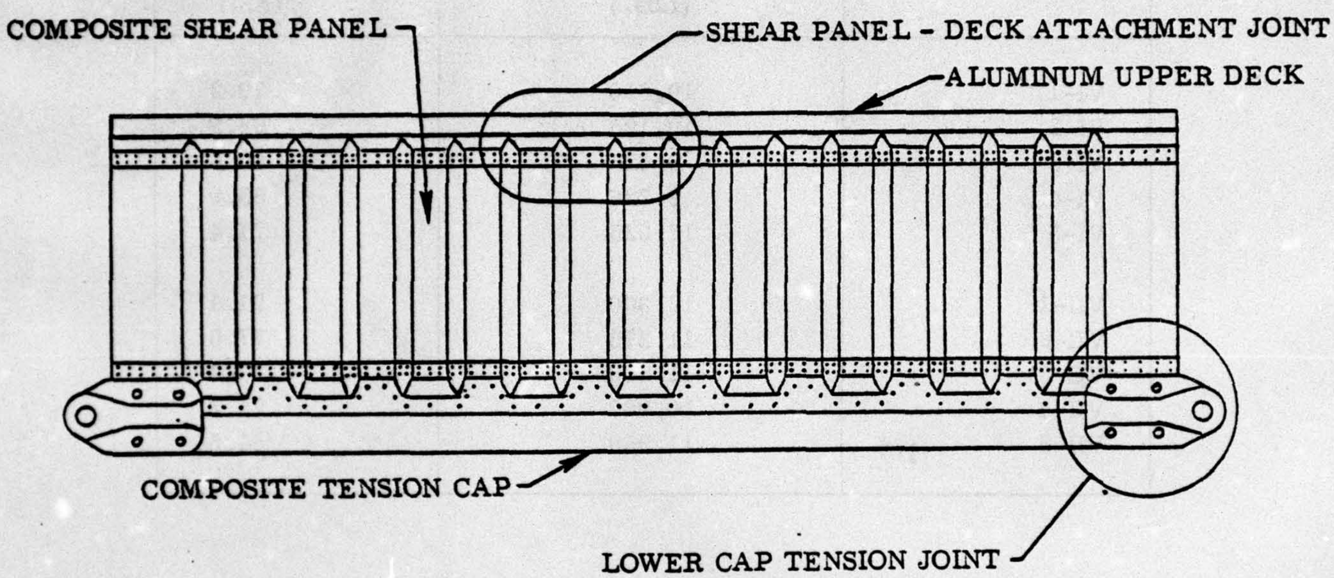


Figure 3.21. Critical Joint Areas of the CTS

3.2.1 LOWER CAP TENSION JOINT TEST ARTICLE.

3.2.1.1 Lower Cap Tension Joint Design. Perhaps the most challenging design task in the entire composite test section design is the highly loaded joint between the graphite/epoxy tension caps and the metal fittings that attach to the bridge ramp sections. After considerable effort investigating alternate joint configurations, a concept was selected that incorporates thin metal interleaves in the ends of the graphite/epoxy cap member to distribute bolt bearing loads uniformly across the section. Subelement tests were conducted to demonstrate the validity of this joint concept before proceeding with detail design of the full scale development article.

The lower tension cap test article drawing is presented in Figure 3.22. This composite cap design was identical to that proposed for the 3-meter CTS except for its reduced length. Significant cost savings were realized by limiting the length of the test article and the test results were independent of specimen length.

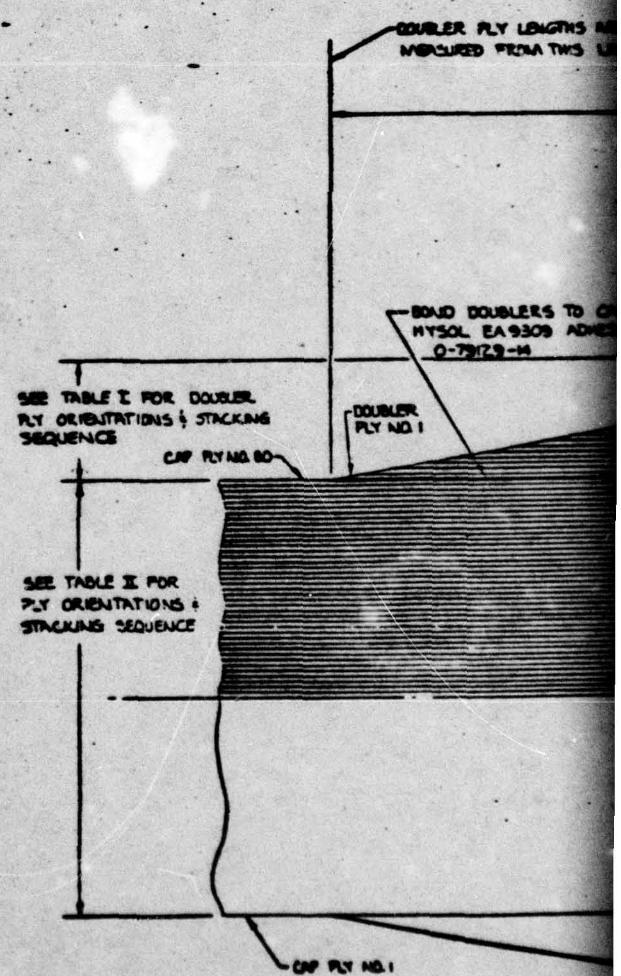
The material system selected for this component was Fiberite's hy-E 1034E. This system incorporates Union Carbide T-300 graphite fibers in a Fiberite 350F cure epoxy matrix. The cured ply thickness is 0.010 inches for a laminate with 65% fiber volume.

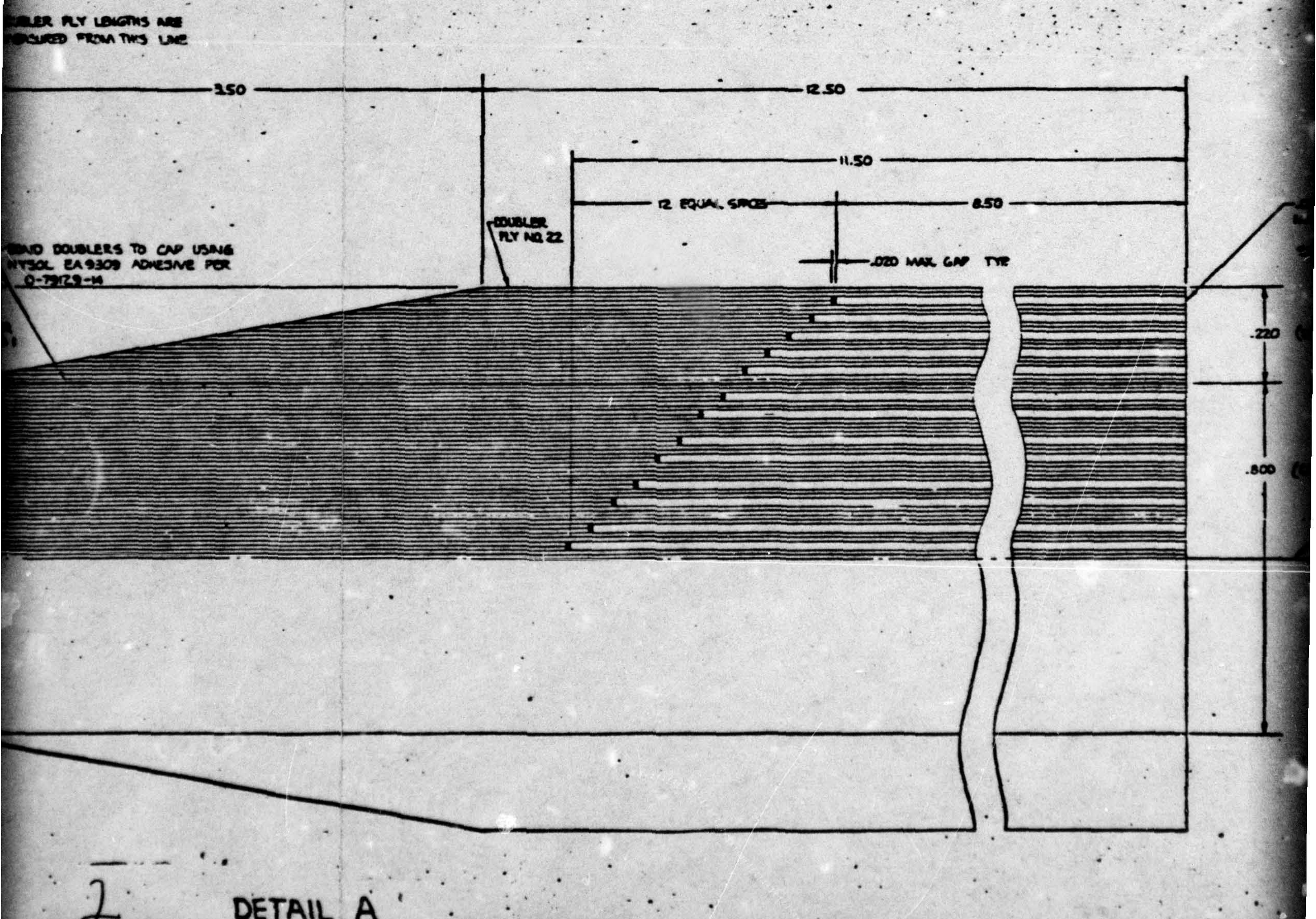
TABLE I
DOUBLER PLY LAYUP

MODULE NO.	PLY NO.	ORIENTATION (DEG)	LENGTH (IN)
D1	1, 2	0, 0	6.00
D2	3, 4	45, 135	6.50
D3	5, 6	0, 0	16.00
D4	7, 8	45, 135	6.75
D5	9, 10	0, 0	16.00
D6	11, 12	45, 135	7.00
D7	13, 14	0, 0	16.00
D8	15, 16	135, 45	7.25
D9	17, 18	0, 0	16.00
D10	19, 20	135, 45	7.50
D11	21, 22	0, 0	16.00

TABLE II
CAP PLY LAYUP

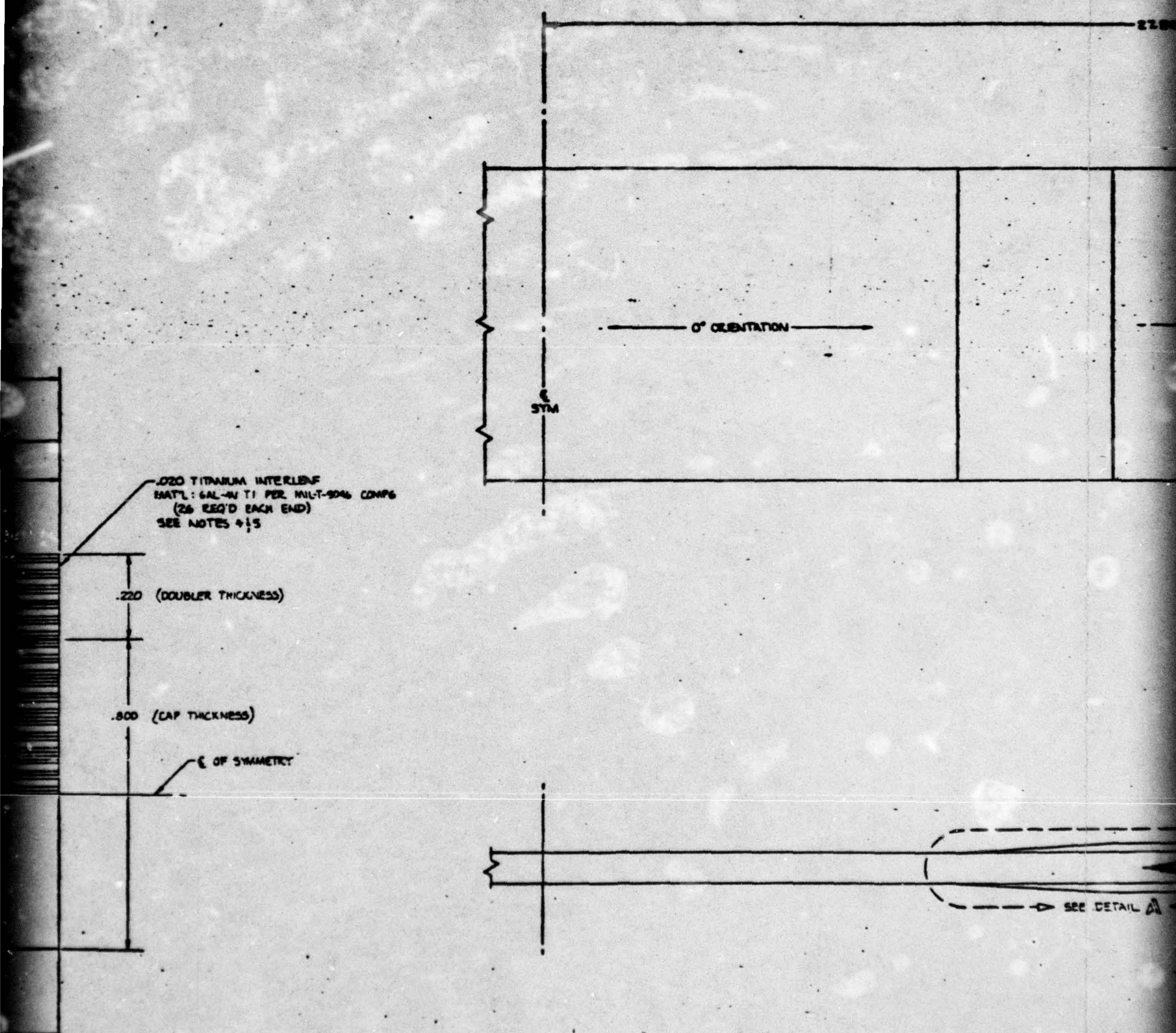
MODULE NO.	PLY NO.	ORIENTATION (DEG)	LENGTH (IN)
C1	1, 2	0, 0	48.00
C2	3, 4	45, 135	29.50
C3	5, 6	0, 0	48.00
C4	7, 8	45, 135	28.00
C5	9, 10, 11, 12	0, 0, 0, 0	48.00
C6	13, 14	45, 135	27.50
C7	15, 16	0, 0	48.00
C8	17, 18	45, 135	27.00
C9	19, 20, 21, 22	0, 0, 0, 0	48.00
C10	23, 24	45, 135	26.50
C11	25, 26	0, 0	48.00
C12	27, 28	45, 135	26.00
C13	29, 30, 31, 32	0, 0, 0, 0	48.00
C14	33, 34	45, 135	25.50
C15	35, 36	0, 0	48.00
C16	37, 38	45, 135	25.00
C17	39, 40, 41, 42	0, 0, 0, 0	48.00
C18	43, 44	135, 45	25.00
C19	45, 46	0, 0	48.00
C20	47, 48	135, 45	25.50
C21	49, 50, 51, 52	0, 0, 0, 0	48.00
C22	53, 54	135, 45	26.00
C23	55, 56	0, 0	48.00
C24	57, 58	135, 45	26.50
C25	59, 60, 61, 62	0, 0, 0, 0	48.00
C26	63, 64	135, 45	27.00
C27	65, 66	0, 0	48.00
C28	67, 68	135, 45	27.50
C29	69, 70, 71, 72	0, 0, 0, 0	48.00
C30	73, 74	135, 45	28.00
C31	75, 76	0, 0	48.00
C32	77, 78	135, 45	29.50
C33	79, 80	0, 0	48.00





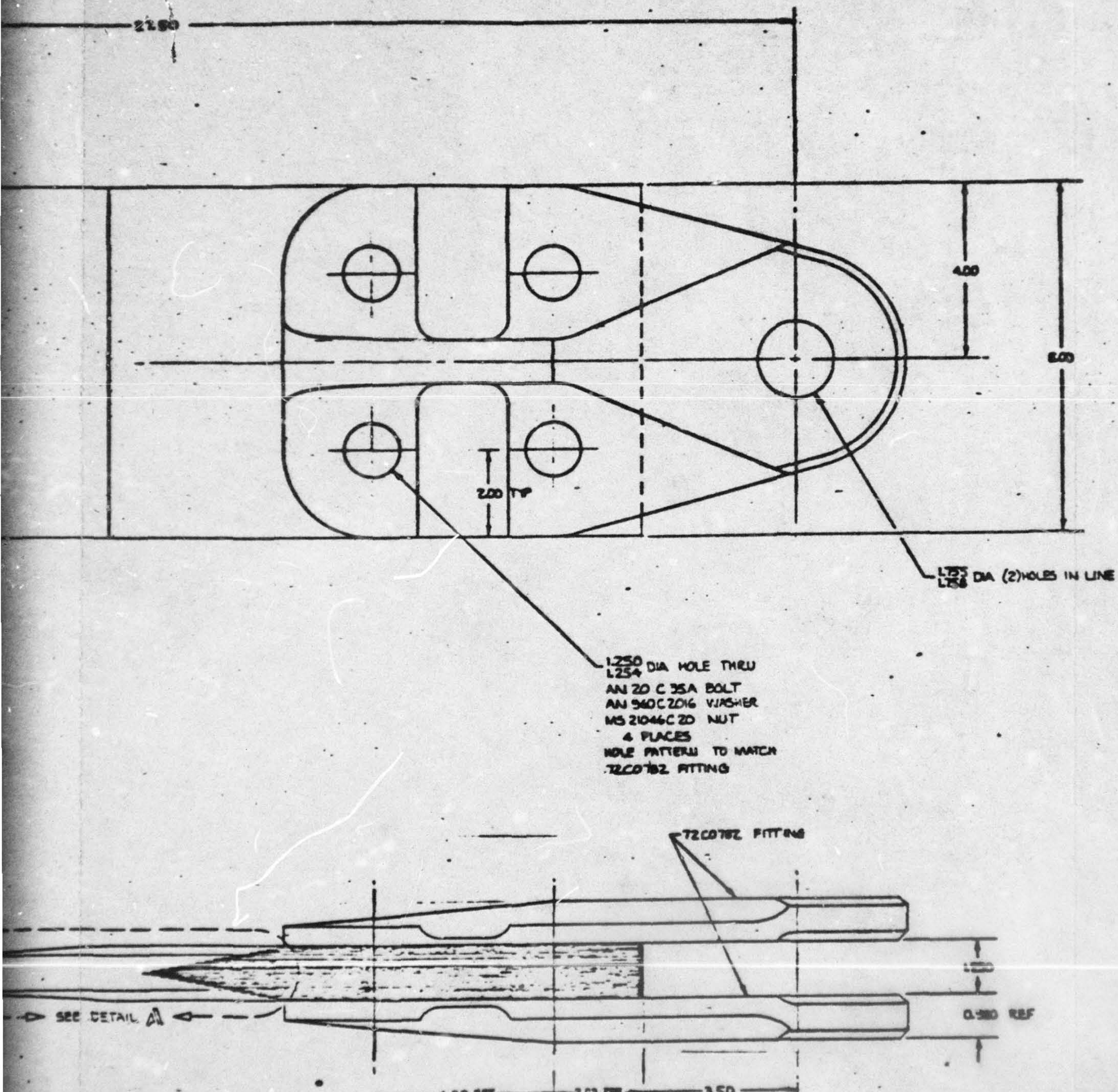
UBLER PLY LENGTHS ARE
ASURED FROM THIS LINE
3.50
12.50
11.50
12 EQUAL SPACES
8.50
DOUBLER PLY NO. 22
BOND DOUBLERS TO CAP USING
HYSOL EA 9309 ADHESIVE PER
D-79129-14
.020 MAX. GAP TYP
.220
.800

2 DETAIL A

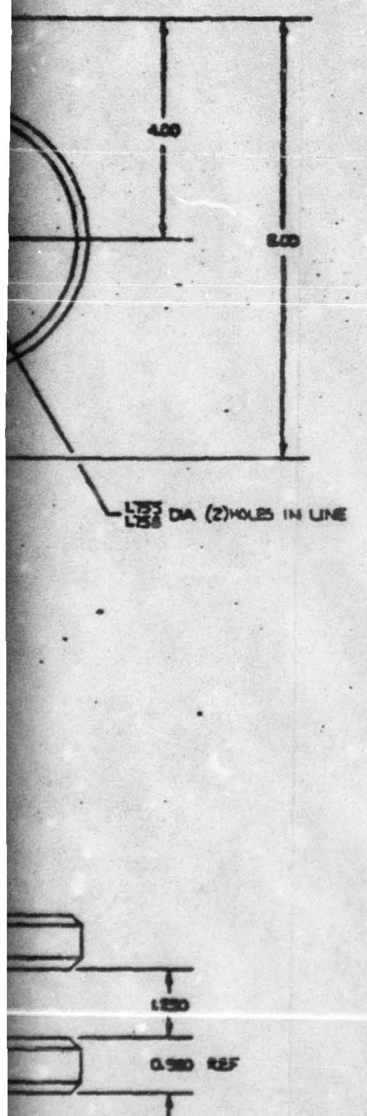


0° ORIENTATION
℄ SYM
.020 TITANIUM INTERLEAF
MAT'L: 6AL-4V TI PER MIL-T-9046 COMP6
(26 REQ'D EACH END)
SEE NOTES 4 & 5
.220 (DOUBLER THICKNESS)
.800 (CAP THICKNESS)
℄ OF SYMMETRY
SEE DETAIL A

3


22.50
4.00
8.00
2.00 TYP
1.253
1.258 DIA (2)HOLES IN LINE
1.250
1.254 DIA HOLE THRU
AN 20 C 35A BOLT
AN 960C2016 WASHER
MS 21046C20 NUT
4 PLACES
HOLE PATTERN TO MATCH
72C0782 FITTING
72C0782 FITTING
SEE DETAIL A
0.980 REF
4.00 REF
2.03 REF
3.50

Fi



NOTES: 1. FABRICATE GRAPHITE/EPOXY CAP PER 72C0780 USING 10-MIL T-300/934 GRAPHITE/EPOXY PREPREG TAPE (FIBERITE hy-E 1034E).
2. DIMENSIONS ARE IN INCHES. TOLERANCES: .XX ±.03 .XXX ±.010
3. MACHINED SURFACES 125/ UNLESS OTHERWISE SPECIFIED.
4. CLEAN TITANIUM INTERLEAVES PER 72C0783.
5. COCURE TITANIUM INTERLEAVES INTO GRAPHITE/EPOXY LAMINATES AS SHOWN. INTERLEAVES REPLACE CROSS PLIES ONLY IN CAP ENDS AND DOUBLERS.

BEST AVAILABLE COPY

Figure 3.22. Tension Cap Joint Development Article

CONVAIR AEROSPACE DIVISION OF GENERAL DYNAMICS
SAN DIEGO, CALIFORNIA

COMPOSITE TEST ARTICLE-
LOWER TENSION CAP

J 14170 72C0781

5

The basic section in the center of the cap was an 8-inch wide, 80 ply $[0_2/\pm45/0_2/\pm45/0_2]_{4s}$ laminate having 60% of the fibers continuous from end to end in the longitudinal direction. The remaining 40% of the plies, in the ±45° orientation, were gradually dropped at the ends of the cap and replaced with 6Al-4V titanium interleaves that were cocured into the composite laminate. Tapered 22-ply doublers containing additional titanium interleaves were bonded to both faces of the basic cap at each end for reinforcement. The doublers were bonded to the cap at room temperature using Hysol EA9309 adhesive. This adhesive system was selected for this application because it possessed good room temperature shear strength and excellent peel strength. The .22-inch thick doublers were tapered to .010 inch over 3.5 inches. This gradual (3.5° angle) taper minimized the axial stress concentration at the doubler ends and the peel stresses in the adhesive bondline.

High-strength steel fittings (Figure 3.23) were bolted to the cap ends for load introduction. Two fittings were attached to each cap end using four 1.25-inch diameter stainless steel bolts. The cap end/fitting configuration was designed to mate with the lower cap fittings of the existing aluminum bridge ramp sections.

3.2.1.2 Lower Tension Cap Structural Analysis. The lower tension cap development article structural analysis is contained in Appendix A.

3.2.1.3 Lower Tension Cap Fabrication. The lower tension cap fabrication sequence is presented in Figure 3.24. Graphite/epoxy prepreg was laid up in large two ply sheets and precompacted and prebled under 50 psi autoclave pressure at 160F. The sheets were then cut to proper size and laid into an aluminum mold tool as shown in Figure 3.25. The mold tool consisted of two flat caul plates on either side of a "picture frame" that was designed to control the finished thickness of the laminate. The tool was vacuum bagged and placed into an autoclave where the laminate was cured under 100 psi at 350F.

Following cure, the laminate was removed from the tool and sawed into two 8-inch wide caps. A special diamond plated wheel was used to saw the laminate to proper width.

The 22-ply doublers were laid up and cured using the same techniques employed for the basic 80-ply cap laminate. Following the diamond saw operation, the doublers were machine tapered and then bonded to the basic caps using Hysol 9309 room temperature cure adhesive.

The cap/doubler assembly was then assembled to the steel end fittings with 1-1/4-inch diameter bolts. The bolt holes were drilled and then bored to final size using conventional machining techniques. The stainless steel bolts were tightened to 600 ft-lb torque and then the 1.75-inch diameter pin holes were bored in-line to final size.

The tension cap test article was then instrumented with ten strain gages and forwarded to the structures test facility.

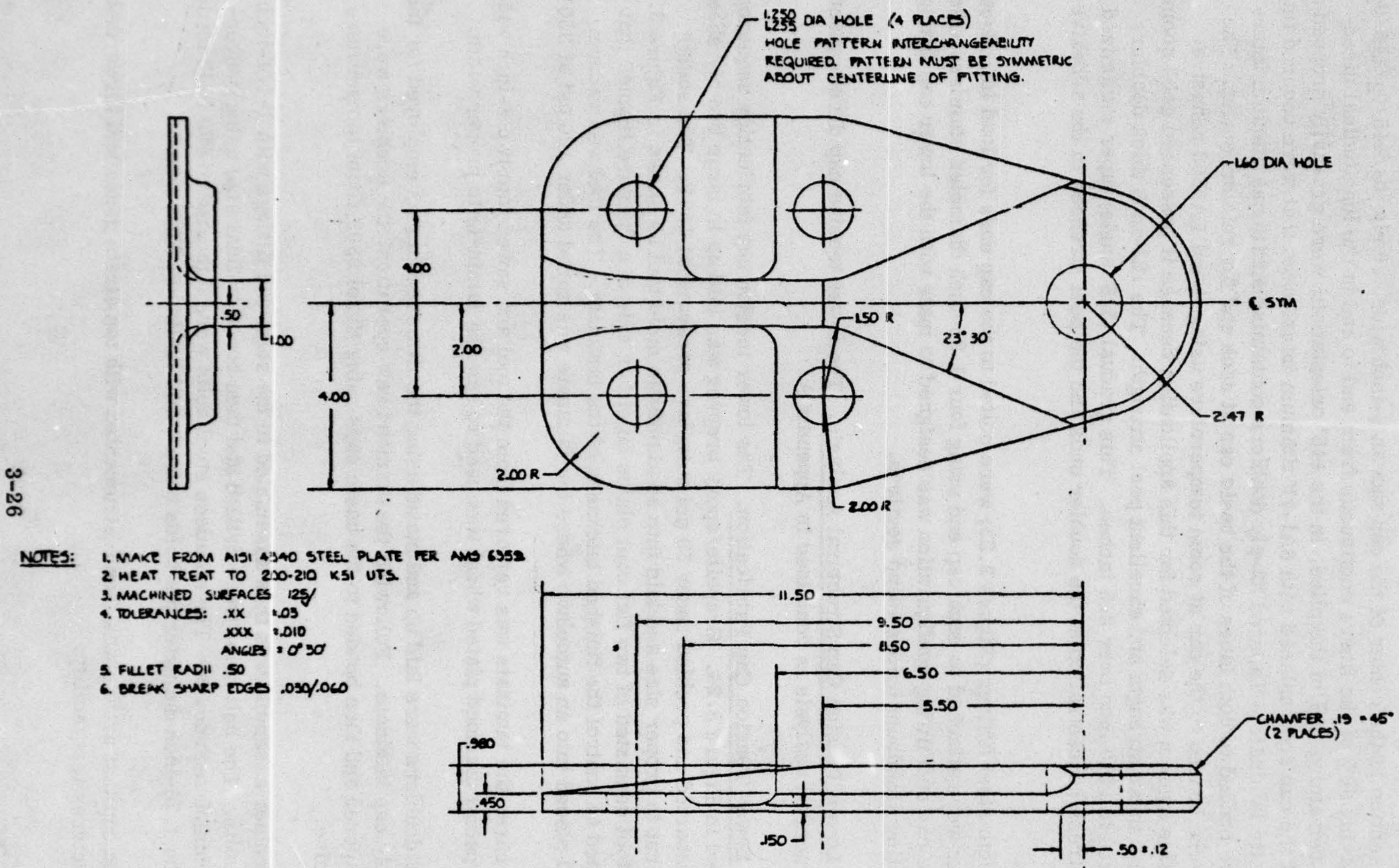


Figure 3.23. Tension Cap End Fitting Design

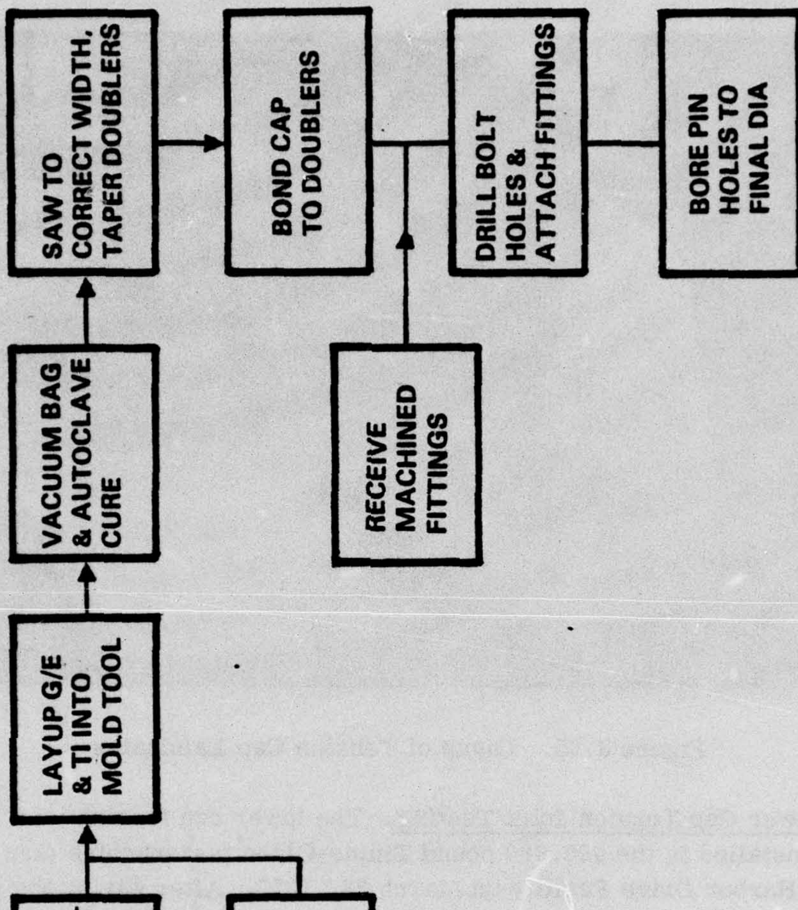


Figure 3.24. Tension Cap Fabrication Sequence

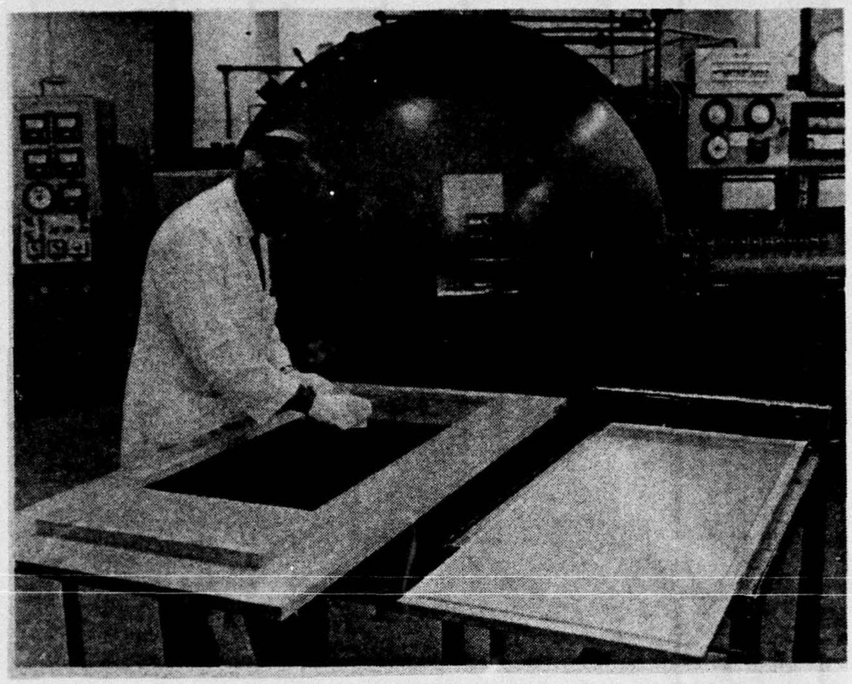


Figure 3.25. Layup of Tension Cap Laminates

3.2.1.4 Lower Cap Tension Joint Testing. The lower cap tension joint static test article was installed in the 600,000 pound Tinius-Olsen test machine (see Figure 3.26) at Convair's Harbor Drive Facility on March 28, 1977. After wiring the strain gages and the extensometer into the recording equipment, the static tension test was initiated. The specimen was loaded in 20,000 pound increments to 500,000 pounds with strain readings taken at each 20,000 pound increment. After taking readings at 500,000 pounds, the load was to have been increased to 520,000 pounds but a test machine malfunction caused the test to be terminated at 517,000 pounds maximum load. During the loading from 0 to 517,000 pounds there was no indication of failure or impending failure of the test specimen.

Strain and deflection readings taken during the static testing are tabulated in Table 3-7. Strain gage locations are shown in Figure 3.27. A load-strain plot is presented in Figure 3.28. Strain gage readings for gage S10 are believed to be erroneous, possibly due to a faulty gage or disbonding of the gage during test. This gage was replaced prior to further testing.

Since the demonstrated static strength of the specimen far surpassed the design load (300,000 pounds), it was decided that no further static testing was necessary. Instead, the static test article was used for fatigue testing. The required fatigue life established for the composite lower tension cap specimen was 15,000 load cycles from a minimum load of 20,000 pounds to a maximum of 200,000 pounds. This is equivalent to 15,000 sixty-ton tank crossings of the 70-foot bridge span with the 3-meter composite test section inserted at the mid-span.

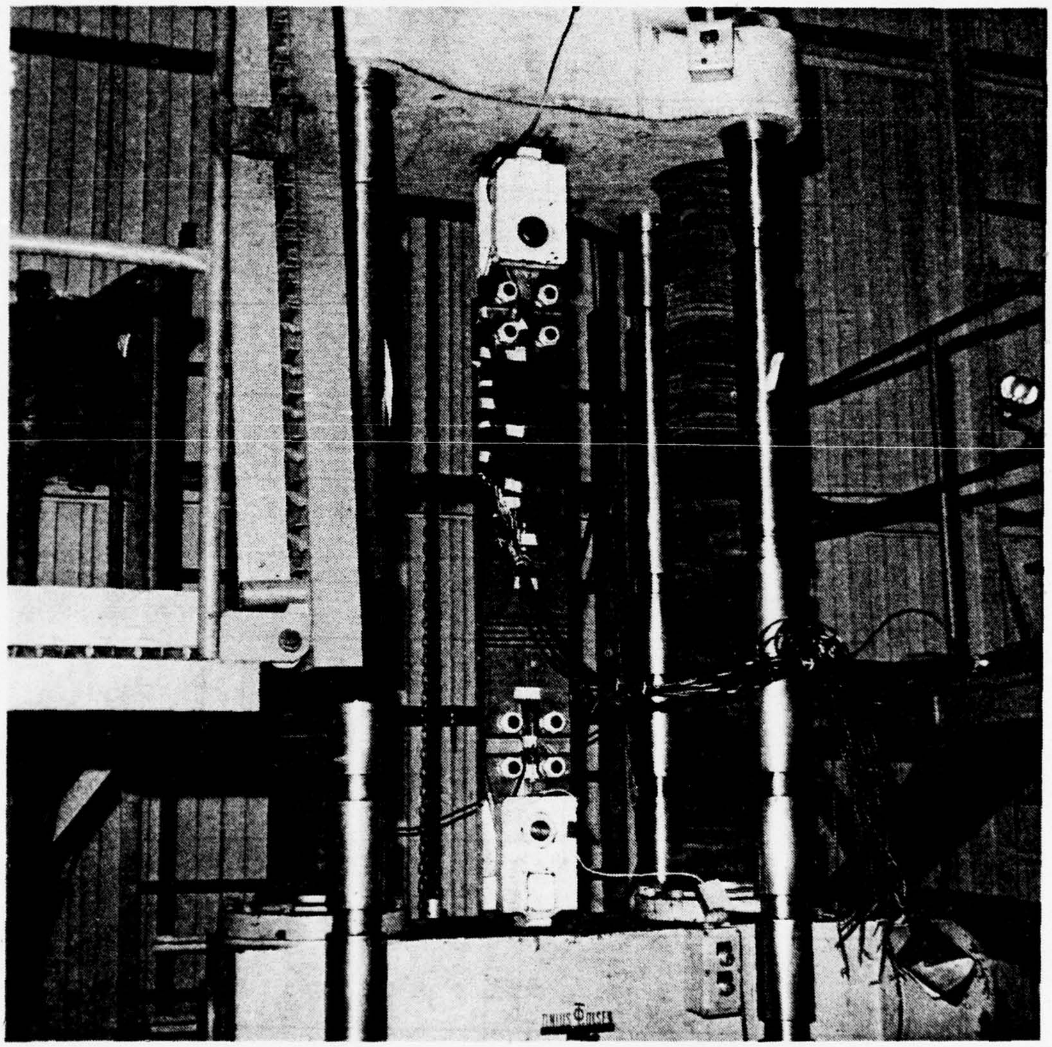
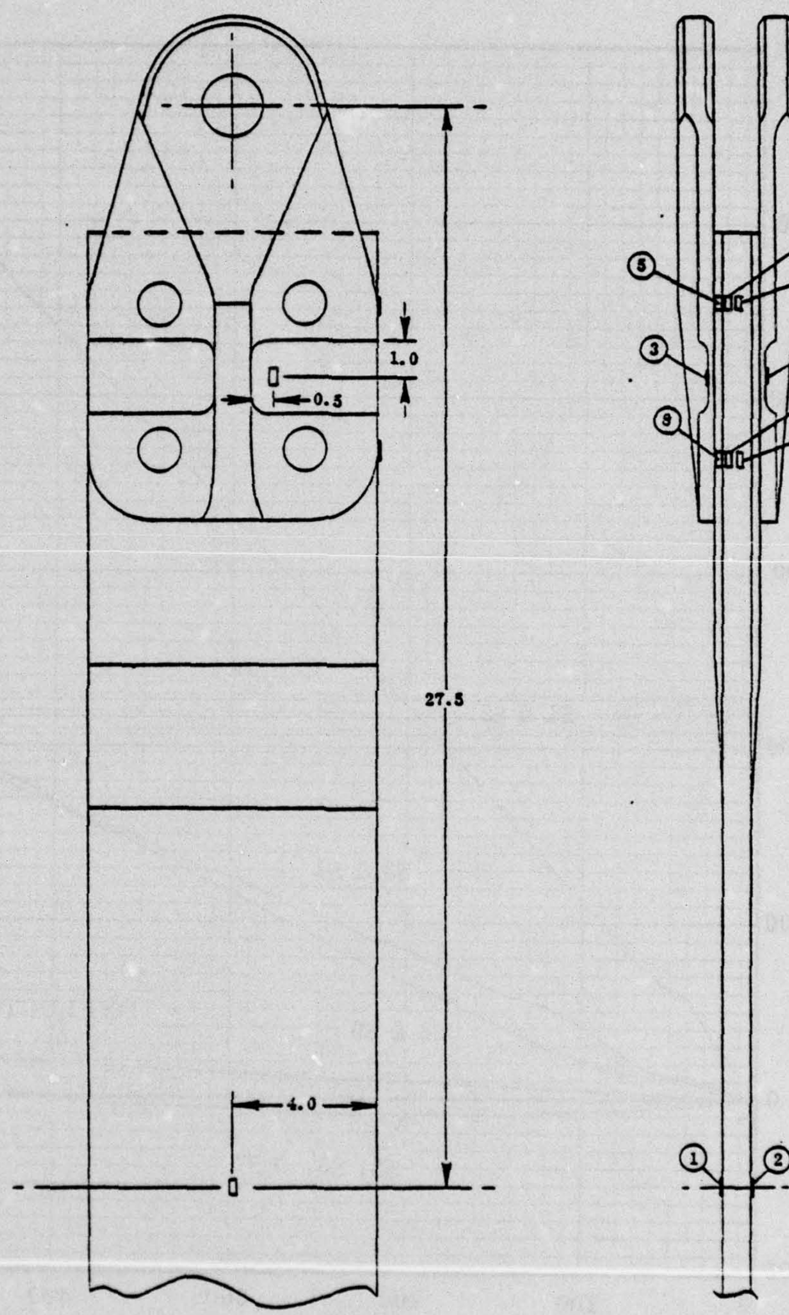


Figure 3.26. Tension Cap Test Setup

Table 3-7. Tension Cap Static Test Strain and Deflection Readings

Load	D	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
20K	+4	+260	+255	+52	+101	-12	+4	+17	+31	+61	-1,332
40K	+21	+571	+562	+117	+191	-34	-14	-24	+107	+139	-1,144
60K	+27	+691	+698	+154	+218	-46	-24	-24	+117	+161	-1,062
80K	+38	+907	+924	+291	+312	-61	-24	-14	+154	+205	-869
100K	+49	+1,131	+1,148	+408	+407	-73	-26	-7	+217	+268	-643
120K	+58	+1,353	+1,365	+515	+501	-85	-29	-9	+298	+369	-399
140K	+67	+1,577	+1,586	+588	+591	-95	-31	-12	+386	+432	-16
160K	+76	+1,808	+1,791	+672	+685	-90	-34	-14	+484	+525	+640
180K	+86	+2,017	+2,022	+742	+770	-93	-34	-12	+582	+615	+669
200K	+94	+2,241	+2,241	+869	+858	-93	-29	-17	+661	+706	+638
220K	+103	+2,446	+2,458	+899	+947	-90	-29	-14	+766	+794	+908
240K	+111	+2,657	+2,670	+1,011	+1,032	-85	-26	-14	+859	+892	+838
260K	+121	+2,896	+2,869	+1,064	+1,124	-81	-29	-7	+962	+1,004	+1,850
280K	+129	+3,103	+3,105	+1,183	+1,212	-73	-14	-4	+1,062	+1,092	+2,103
300K	+138	+3,317	+3,317	+1,265	+1,294	-68	-9	+7	+1,170	+1,190	+2,194
320K	+146	+3,534	+3,531	+1,335	+1,379	-56	0	+9	+1,258	+1,290	+2,194
350K	+159	+3,860	+3,855	+1,470	+1,512	-41	+4	+21	+1,415	+1,437	+2,818
360K	+163	+3,979	+3,962	+1,527	+1,553	-41	+29	+26	+1,486	+1,488	+2,396
380K	+172	+4,179	+4,169	+1,572	+1,638	-22	+29	+36	+1,569	+1,581	+2,336
400K	+181	+4,398	+4,390	+1,664	+1,728	-7	+56	+48	+1,689	+1,698	+2,028
420K	+189	+4,602	+4,602	+1,744	+1,813	+14	+60	+63	+1,802	+1,803	+2,160
440K	+200	+4,824	+4,819	+1,861	+1,907	+31	+77	+75	+1,895	+1,911	+2,840
470K	+213	+5,145	+5,135	+1,963	+2,041	+61	+109	+99	+2,066	+2,082	+5,721
480K	+217	+5,252	+5,245	+2,030	+2,087	+78	+121	+109	+2,128	+2,143	+10,127
500K	+227	+5,461	+5,452	+2,088	+2,169	+103	+143	+126	+2,243	+2,277	+10,813



Notes:

1. Gages 3 & 4 are Baldwin-Lima Hamilton (BLH) type FAE-25-12-S6. All other gages are BLH type FAE-25-12-S1.

Figure 3.27. Tension Cap Strain Gage Locations (static test article)

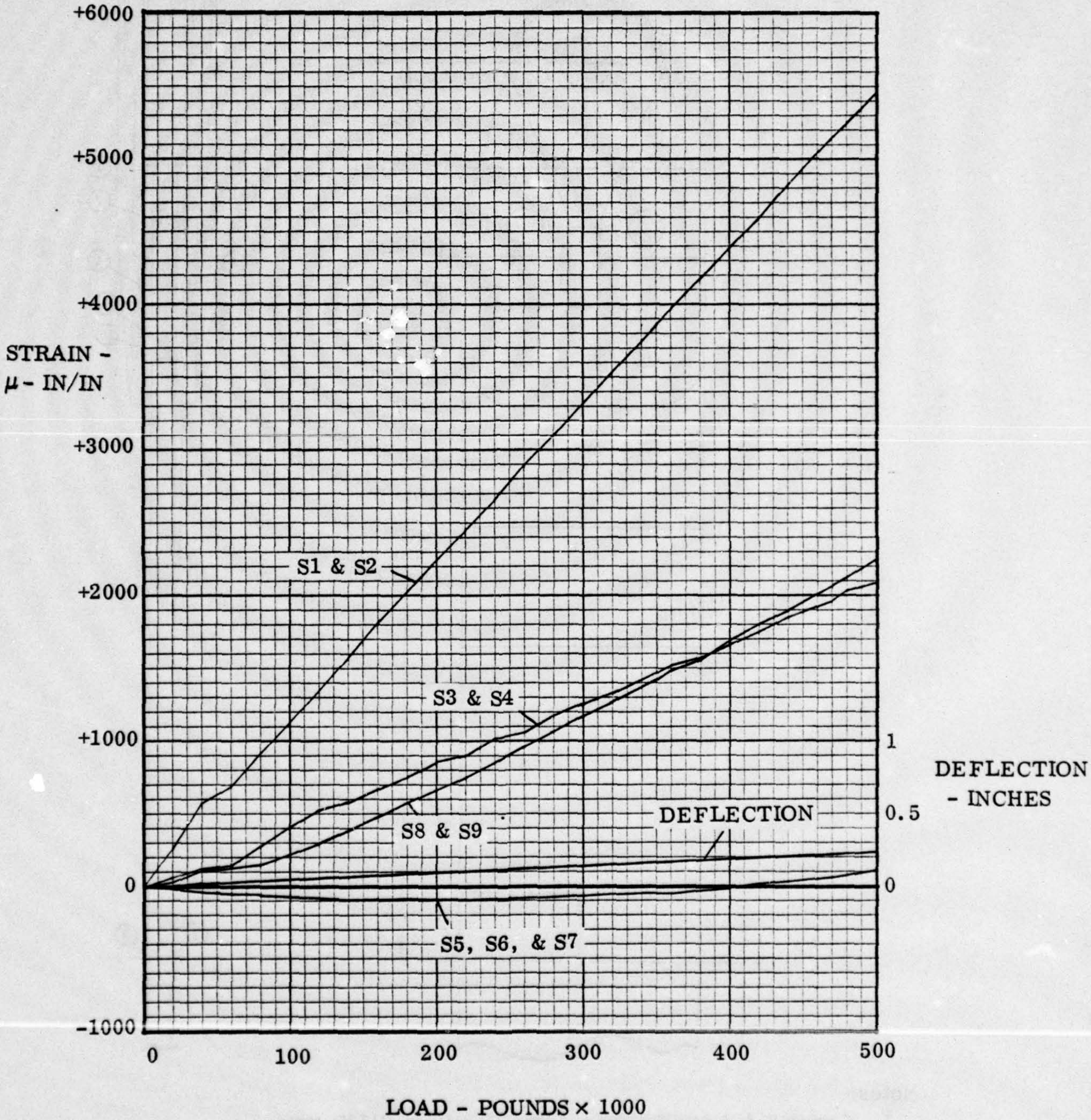


Figure 3.28. Tension Cap Static Test Load-Strain Plots

Strain and deflection readings taken periodically during the fatigue testing are presented in Table 3-8. The strain readings are very close to the strain readings obtained during the static test possibly due to slippage between the steel fittings and the tension cap. No indications of tension cap degradation could be seen in the strain gage readings or by visual inspection of the component after fatigue.

Table 3-8. Tension Cap Fatigue Test Strain and Deflection Readings

Cycle	Load	D	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
2,803	40K	—	+569	+467	+356	+184	-14	+7	+17	+97	+89	+163
2,804	60K	+8	+781	+676	+446	+256	-17	+19	+21	+161	+164	+233
2,805	80K	+10	+1,000	+881	+495	+329	-14	+21	+31	+232	+233	+305
2,806	100K	+18	+1,219	+1,087	+568	+392	-22	+19	+34	+293	+299	+375
2,807	120K	+25	+1,445	+1,309	+677	+467	-14	+21	+36	+374	+372	+452
2,808	140K	+34	+1,674	+1,528	+779	+559	-29	+14	+31	+445	+442	+520
2,809	160K	+41	+1,886	+1,723	+852	+654	-36	+7	+26	+516	+511	+592
2,810	180K	+46	+2,107	+1,944	+922	+758	-39	+12	+21	+602	+586	+667
7,000	40K	+10	+542	+460	+216	+206	-9	-9	+7	+93	+122	+161
7,001	60K	+15	+739	+642	+274	+278	-14	0	+19	+161	+188	+231
7,002	80K	+23	+980	+868	+361	+358	-9	+9	+29	+247	+266	+310
7,003	100K	+28	+1,195	+1,070	+421	+426	-12	+7	+31	+315	+334	+383
7,004	120K	+36	+1,414	+1,280	+555	+492	-14	+12	+29	+384	+402	+452
7,005	140K	+43	+1,635	+1,494	+647	+569	-24	+7	+31	+460	+475	+522
7,006	160K	+50	+1,857	+1,698	+755	+671	-27	-2	+29	+531	+548	+602
7,007	180K	+58	+2,076	+1,915	+782	+765	-34	-7	+24	+607	+619	+676
9,012	40K	+10	+479	+408	+159	+181	+9	-2	+34	+90	+131	+161
9,013	60K	+16	+693	+601	+216	+252	+14	-7	+48	+161	+178	+231
9,014	80K	+19	+929	+827	+284	+332	+17	+4	+51	+235	+263	+313
9,015	100K	+30	+1,161	+1,032	+351	+409	+9	+19	+56	+313	+336	+390
9,016	120K	+33	+1,387	+1,265	+453	+475	+17	+4	+56	+394	+430	+464
9,017	140K	+40	+1,608	+1,479	+540	+555	+7	+9	+56	+467	+480	+534
9,018	160K	+49	+1,837	+1,698	+647	+654	+2	+4	+46	+543	+558	+611
9,019	180K	+55	+2,042	+1,896	+740	+751	-4	-2	+51	+619	+624	+684
13,673	40K	+10	+535	+442	+244	+213	-4	+114	+12	+88	+63	+161
13,674	60K	+16	+776	+640	+291	+295	0	+119	+21	+168	+146	+243
13,675	80K	+23	+985	+871	+348	+361	-2	+126	+21	+242	+233	+313
13,676	100K	+29	+1,195	+1,068	+443	+431	-4	+133	+29	+311	+280	+387
13,677	120K	+37	+1,428	+1,290	+538	+501	-9	+133	+31	+386	+372	+457
13,678	140K	+43	+1,630	+1,489	+630	+569	-14	+119	+21	+453	+438	+525
13,679	160K	+51	+1,869	+1,711	+715	+666	-19	+114	+19	+533	+518	+607
13,680	180K	+59	+2,093	+1,927	+822	+765	-29	+121	+14	+609	+581	+679
14,971	40K	+9	+501	+408	+191	+196	+9	+129	+34	+117	+77	+168
14,972	60K	+15	+732	+640	+291	+278	+22	+133	+36	+178	+157	+250
14,973	80K	+21	+944	+842	+351	+344	+22	+138	+46	+249	+226	+317
14,974	100K	+27	+1,158	+1,053	+436	+414	+17	+141	+48	+320	+299	+387
14,975	120K	+33	+1,384	+1,260	+525	+482	+9	+141	+48	+394	+381	+462
14,976	140K	+42	+1,606	+1,443	+618	+559	0	+138	+51	+477	+435	+539
14,977	160K	+48	+1,825	+1,686	+675	+649	+2	+131	+48	+541	+508	+611
14,978	180K	+56	+2,056	+1,908	+772	+756	-7	+126	+43	+629	+586	+691

Following the 15,000 fatigue cycles, a residual strength test was run. The specimen was loaded to failure in tension with strain and deflection readings taken at 20,000-pound increments of load. Failure occurred in the graphite/epoxy doublers at a load of 515,000 pounds. The failure mode, shown in Figures 3.29 and 3.30, was interlaminar shear failure of the [±45] doubler plies closest to the cap - doubler bond. The adhesive bond itself did not fail.

Strain and deflection readings taken during the residual strength test are listed in Table 3-9. These readings are essentially the same as those recorded during the static test performed earlier.

3.2.2 CORRUGATED PANEL/DECK JOINT TEST ARTICLE.

3.2.2.1 Corrugated Panel Design. The shear panel-deck attachment joint test article design is presented in Figure 3.31. This specimen represents a section of one shear panel taken from the center of the 3-meter composite test section. The upper edge of the corrugated composite panel is attached to a machined edge member using room temperature cure adhesive and mechanical fasteners. In production, this edge member would be inexpensively formed from flat sheet material in lieu of machining. The lower edge of the panel is bonded and mechanically fastened to a strip of corrugated aluminum sheet. After assembly, the edge members are machined parallel and perpendicular to the panel sides.

The corrugated composite panel is comprised of an 0.080-inch thick laminated graphite/epoxy core with 0.014-inch thick Kevlar/epoxy cloth faces. The Kevlar faces are provided for protection against damage of the graphite/epoxy and corrosion of the aluminum edge member.

3.2.2.2 Corrugated Panel Structural Analysis. The structural analysis of the corrugated panel/deck joint test article is contained in Appendix A of this report.

3.2.2.3 Corrugated Panel Fabrication. The graphite/Kevlar/epoxy corrugated panel was laid up in 2-ply modules on a low-cost aluminum mold tool as shown in Figure 3.32. The tool was fabricated from sheet aluminum using a bend-on-brake technique. Following layup, the laminate was vacuum-bagged and cured in an autoclave under 100 psi at 350F. The cured panel was trimmed to size on a band saw and then bonded to the upper and lower edge members at room temperature using Hysol 9309 adhesives. Following cure of the adhesive, 3/16-inch diameter titanium "cherry buck" rivets were installed through the edge members and the composite panel. The upper and lower faces of the edge members were machined parallel prior to installing strain gages for test.

3.2.2.4 Corrugated Panel Testing. The corrugated panel test article was installed in the 200,000 pound test machine, as shown in Figure 3.33, at the Kearny Mesa facility on March 29, 1977. The panel was loaded to failure in compression with

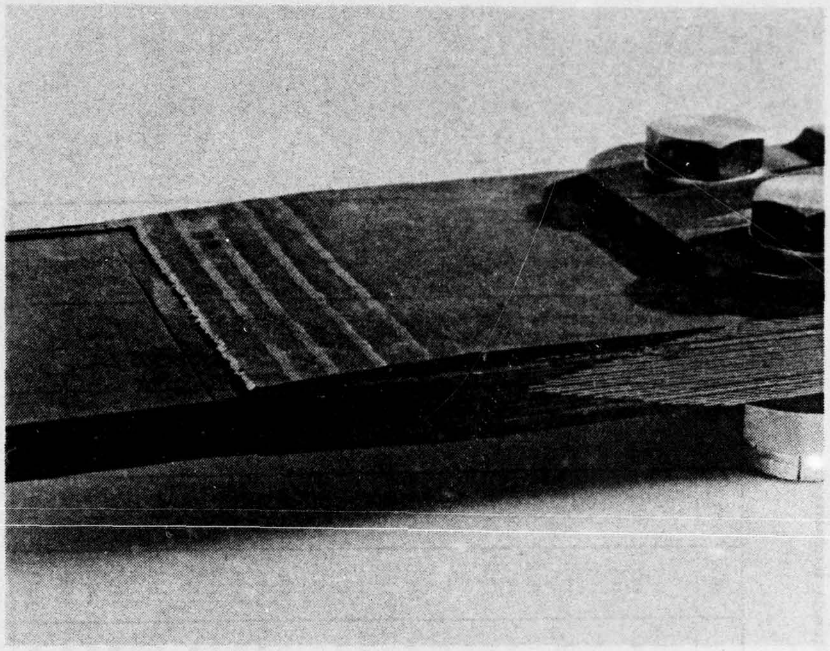


Figure 3.29. Failed Tension Cap Test Specimens

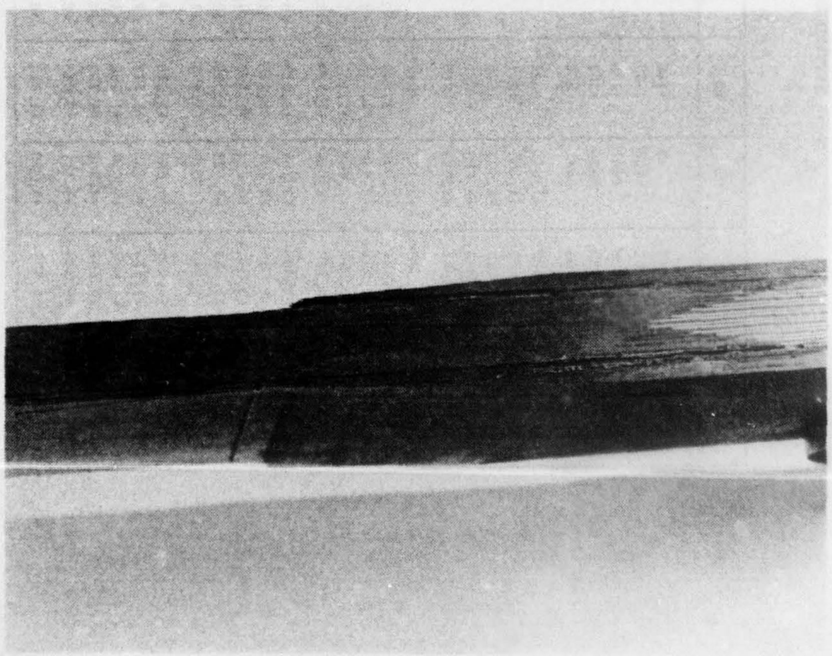
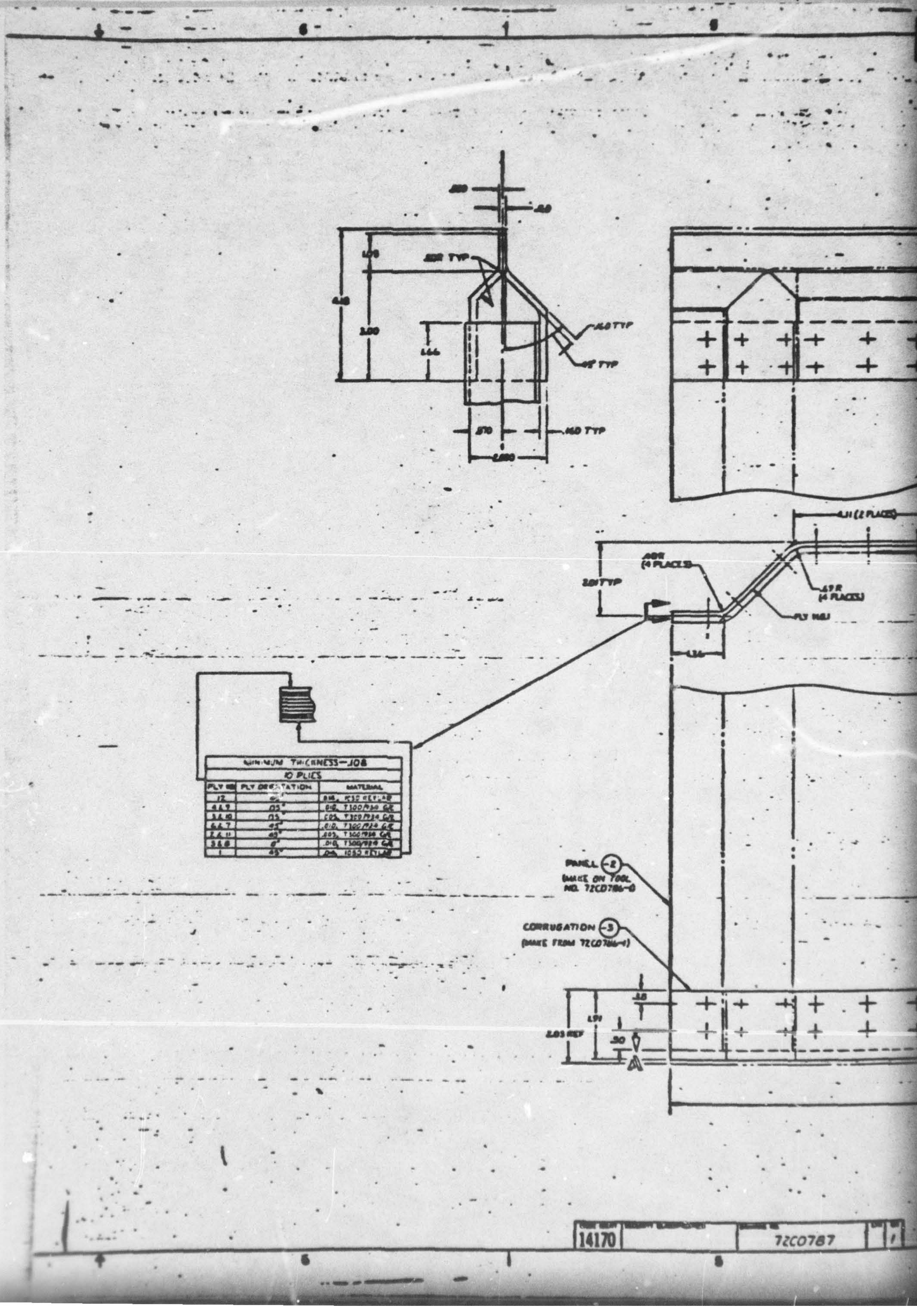


Figure 3.30. Tension Cap Failure Mode

Table 3-9. Tension Cap Residual Strength Test
Strain and Deflection Readings

Load	D	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0	-2	+7	+9	-109	+31	+17	+82	+2	+2	-35	+7
20K	0	+262	+197	-77	+140	+12	+82	+21	+17	+11	+86
40K	+6	+498	+401	+39	+208	+12	+90	+21	+93	+84	+163
60K	+12	+732	+620	+161	+283	+12	+85	+29	+164	+181	+243
80K	+18	+954	+837	+256	+353	+12	+90	+34	+232	+221	+308
100K	+26	+1,182	+1,049	+341	+416	+7	+85	+34	+298	+289	+380
120K	+34	+1,409	+1,265	+451	+484	0	+85	+34	+369	+360	+457
140K	+40	+1,635	+1,460	+570	+576	-22	+82	+29	+423	+428	+529
160K	+48	+1,859	+1,698	+687	+678	-29	+80	+24	+531	+492	+599
180K	+56	+2,081	+1,913	+812	+782	-29	+75	+19	+597	+579	+676
200K	+64	+2,300	+2,127	+917	+877	-34	+75	+19	+675	+654	+754
220K	+74	+2,521	+2,339	+1,024	+969	-36	+90	+14	+768	+725	+833
240K	+82	+2,735	+2,536	+1,054	+1,068	-36	+75	+17	+857	+817	+917
260K	+92	+2,954	+2,769	+1,103	+1,161	-34	+77	+14	+928	+904	+1,002
280K	+101	+3,169	+2,984	+1,128	+1,253	-27	+77	+21	+1,035	+991	+1,093
300K	+109	+3,385	+3,195	+1,218	+1,345	-19	+90	+31	+1,126	+1,080	+1,185
320K	+118	+3,599	+3,407	+1,275	+1,435	-14	+95	+36	+1,219	+1,179	+1,276
340K	+126	+3,806	+3,624	+1,330	+1,517	-2	+104	+36	+1,315	+1,264	+1,370
360K	+135	+4,033	+3,828	+1,390	+1,609	+4	+126	+53	+1,415	+1,363	+1,464
380K	+144	+4,249	+4,047	+1,455	+1,701	+24	+126	+68	+1,515	+1,453	+1,565
400K	+152	+4,459	+4,252	+1,510	+1,788	+31	+141	+75	+1,613	+1,573	+1,659
420K	+160	+4,673	+4,449	+1,572	+1,878	+49	+155	+90	+1,711	+1,650	+1,756
440K	+169	+4,889	+4,697	+1,692	+1,963	+61	+165	+97	+1,819	+1,749	+1,866
460K	+177	+5,104	+4,902	+1,786	+2,050	+81	+180	+112	+1,920	+1,851	+1,965
480K	+186	+5,325	+5,111	+1,883	+2,140	+95	+197	+124	+2,022	+1,952	+2,064
500K	+194	+5,527	+5,323	+1,978	+2,225	+113	+214	+136	+2,130	+2,048	+2,165



MINIMUM THICKNESS—.108
10 PLIES
PLY NO.
PLY ORIENTATION
MATERIAL
.160 TYP
.570
2.00
1.66
4.11 (2 PLACES)
(4 PLACES)
PLY NO.1
PANEL -2
(MAKE ON TOOL
NO. 72CD786-0
CORRUGATION -3
(MAKE FROM 72CD786-1)
2.03 REF
.30
14170
72C0787

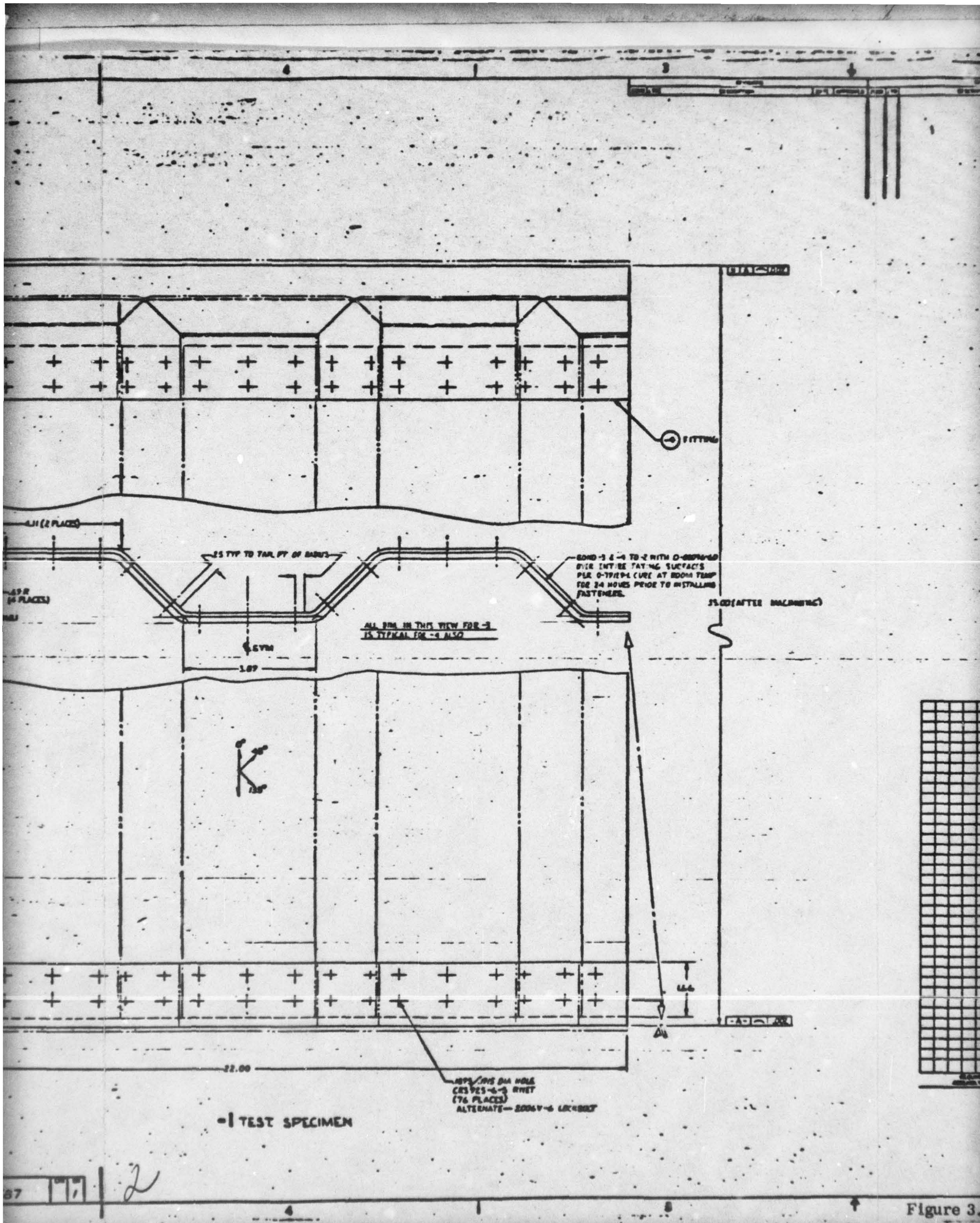

FITTING
.25 TYP TO TAN PT OF RADIUS
ALL DIM IN THIS VIEW FOR -2
IS TYPICAL FOR -4 ALSO
3.87
22.00
(76 PLACES)
-1 TEST SPECIMEN

Figure 3.

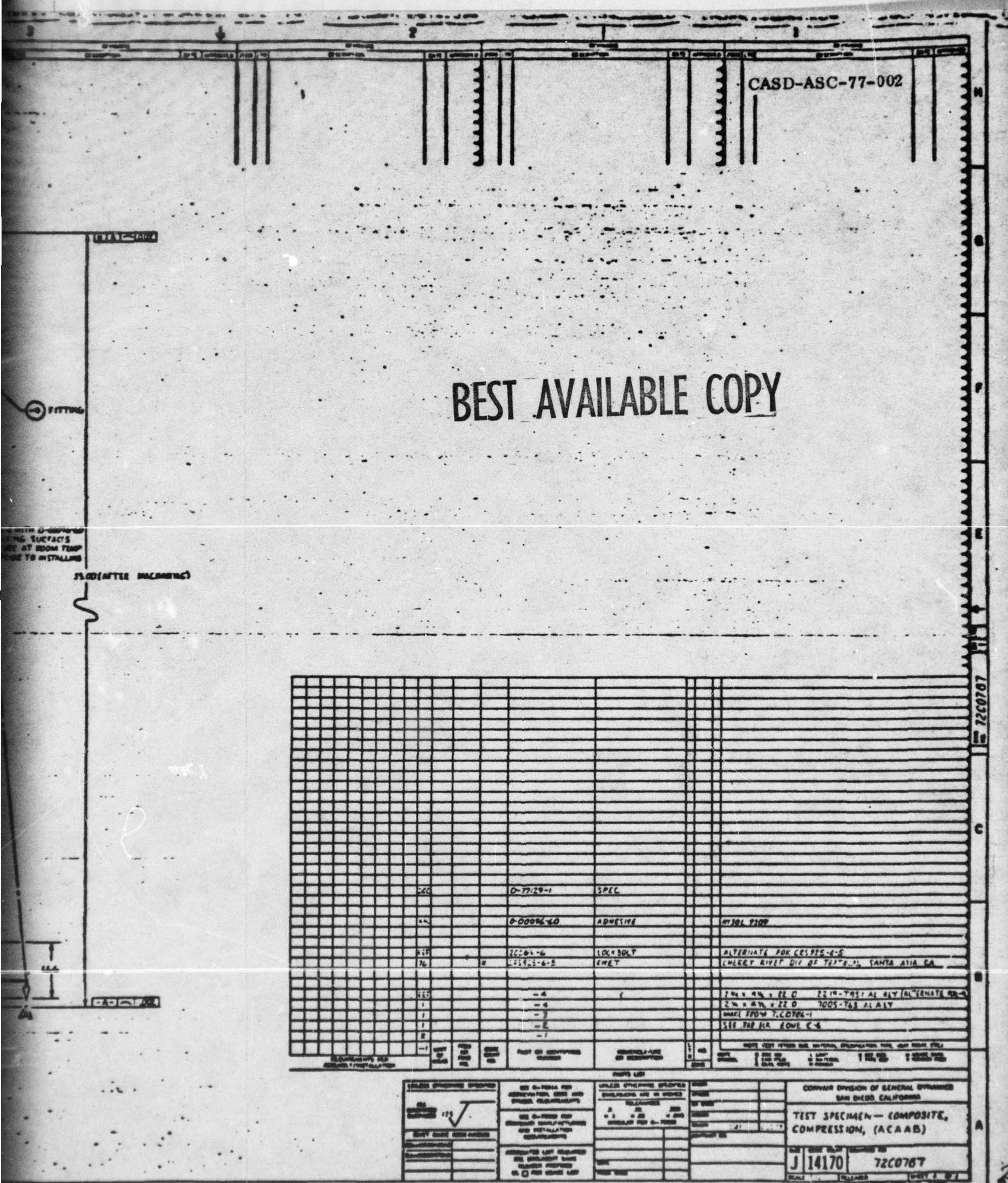


Figure 3.31. Shear Panel-Deck Joint Development Article

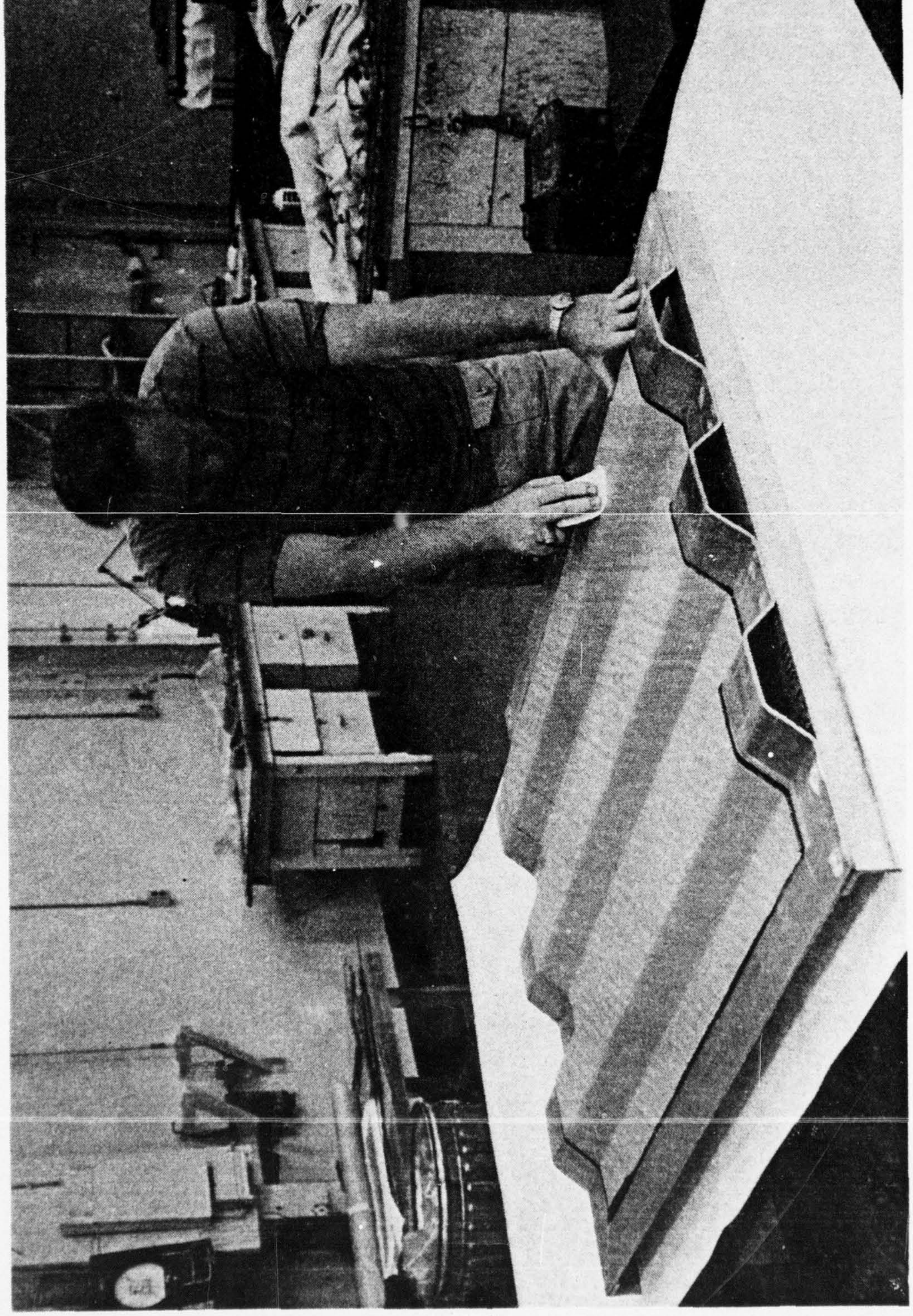


Figure 3-32. Layup of Corrugated Panel

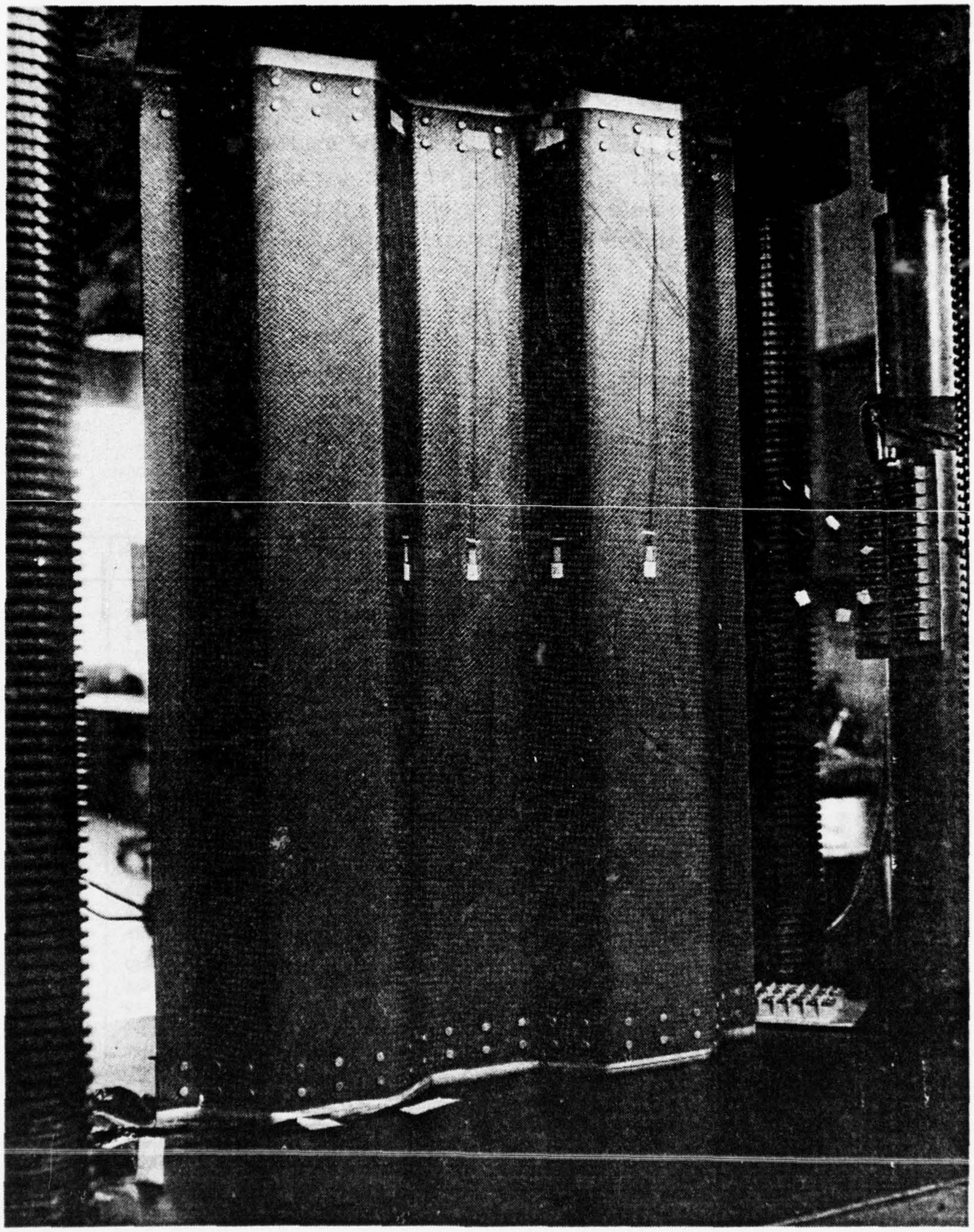


Figure 3.33. Corrugated Panel Installed in Test Machine

strain readings taken at 1000 pound increments of load. The strain readings taken during this test are listed in Table 3-10 and presented graphically in Figure 3.34. Strain gage locations are shown in Figure 3.35.

The panel test was uneventful up to about 18,000 pounds when the adhesive filler at the lower edge attachment disbonded from the aluminum edge member. From this point on the load was carried solely by the rivets. The load was increased beyond 21,000 pounds where the annealed lower edge member began yielding around the rivet holes. The load could not be held constant beyond this point and strain readings taken are not as accurate as those taken before the yielding began.

Final failure occurred at 34,150 pounds. One edge of the panel buckled and delaminated as shown in Figure 3.36. At the moment of failure, the panel was bowed approximately one inch out of plane due to the beam-column loading.

Table 3-10. Corrugated Panel Compression Test Strain Readings

Load	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
1,000	-14	+4	-14	-86	-28	-23	-48	-280	-74	-74	-54	-54
2,000	-32	+24	-88	-180	-72	-68	-112	-356	-154	-158	-124	-128
3,000	-48	+50	-186	-446	-122	-116	-162	-422	-222	-232	-192	-200
4,000	-58	+70	-280	-538	-160	-158	-216	-480	-288	-302	-254	-268
5,000	-66	+84	-352	-670	-216	-216	-270	-556	-352	-374	-304	-332
6,000	-68	+92	-424	-802	-272	-276	-330	-614	-412	-438	-374	-398
7,000	-70	+100	-494	-882	-330	-338	-388	-678	-470	-502	-432	-462
8,000	-66	+108	-560	-968	-386	-394	-444	-734	-526	-564	-488	-524
9,000	-60	+112	-628	-1,040	-444	-454	-500	-780	-582	-626	-544	-584
10,000	-54	+114	-696	-1,128	-502	-516	-554	-830	-638	-690	-602	-648
11,000	-48	+122	-762	-1,384	-556	-574	-610	-902	-692	-752	-660	-712
12,000	-42	+122	-830	-1,474	-614	-634	-666	-966	-746	-814	-716	-774
13,000	-34	+120	-896	-1,560	-670	-694	-720	-1,024	-800	-874	-772	-834
14,000	-28	+120	-966	-1,642	-730	-754	-774	-1,084	-854	-934	-830	-894
15,000	-20	+118	-1,034	-1,720	-788	-820	-828	-1,146	-908	-996	-890	-960
16,000	-12	+116	-1,104	-1,802	-848	-882	-888	-1,210	-962	-1,058	-950	-1,026
17,000	0	+112	-1,168	-1,876	-912	-950	-950	-1,282	-1,020	-1,126	-986	-1,072
18,000	+8	+114	-1,236	-2,634	-970	-1,012	-1,004	-1,408	-1,072	-1,184	-1,040	-1,132
19,000	+16	+112	-1,302	-2,514	-1,024	-1,074	-1,058	-1,476	-1,124	-1,246	-1,092	-1,192
20,000	+24	+112	-1,370	-2,642	-1,082	-1,136	-1,116	-1,536	-1,176	-1,304	-1,148	-1,250
21,000	+32	+110	-1,412	-2,428	-1,112	-1,162	-1,010	-1,418	-964	-998	-962	-916
25,000	+116	+48	-1,828	-3,832	-1,436	-1,602	-1,390	-4,002	-1,082	-1,202	-1,470	-1,612
26,000	+130	+45	-1,930	-3,560	-1,530	-1,705	-1,475	-4,850	-1,100	-1,214	-1,572	-1,714
27,000	+150	+35	-2,035	-3,590	-1,640	-1,830	-1,575	-4,970	-1,100	-1,210	-1,718	-1,836
28,000	+185	+15	-2,185	-3,735	-1,845	-2,055	-1,740	-5,170	-1,070	-1,172	-1,926	-2,020

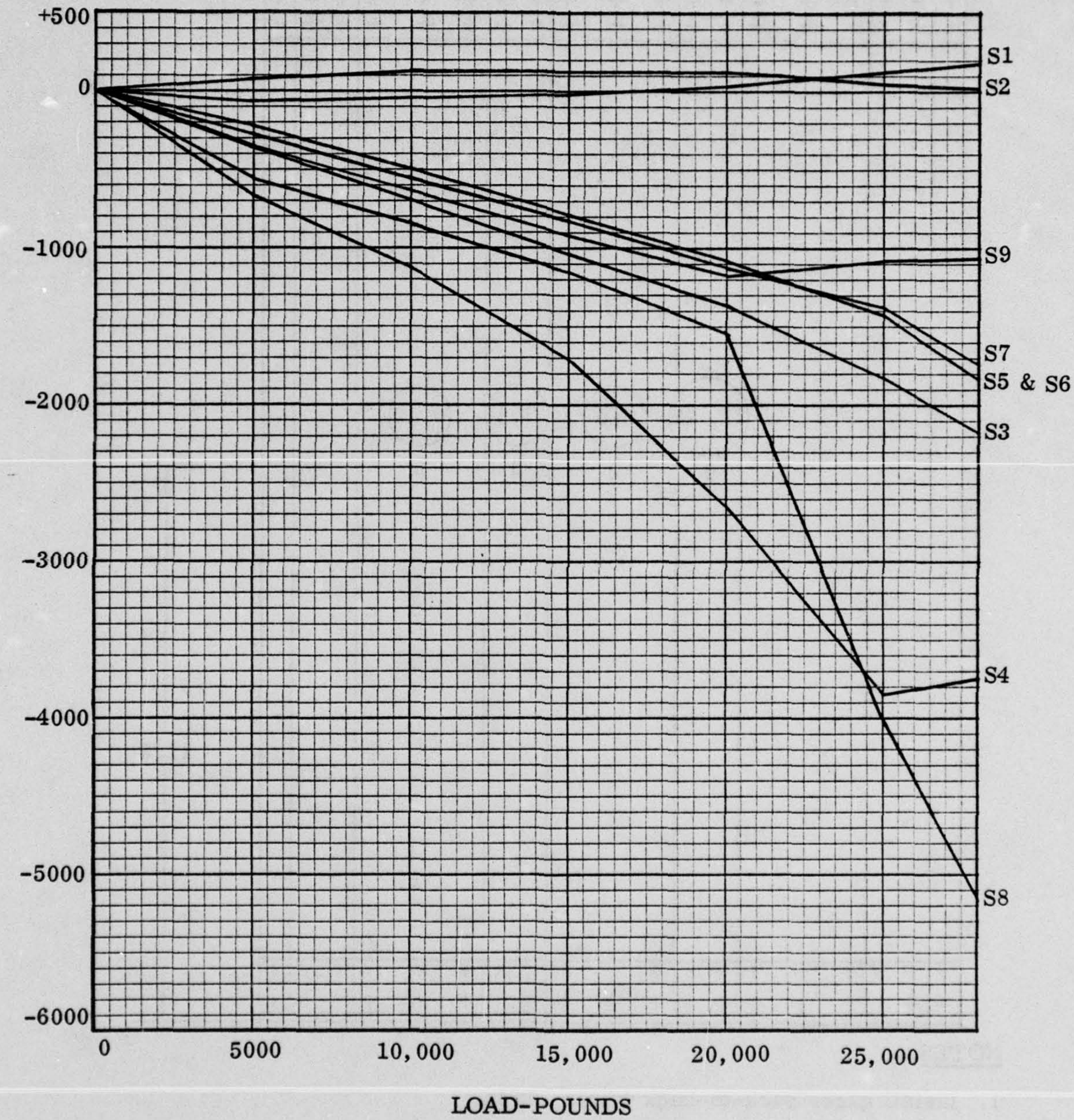
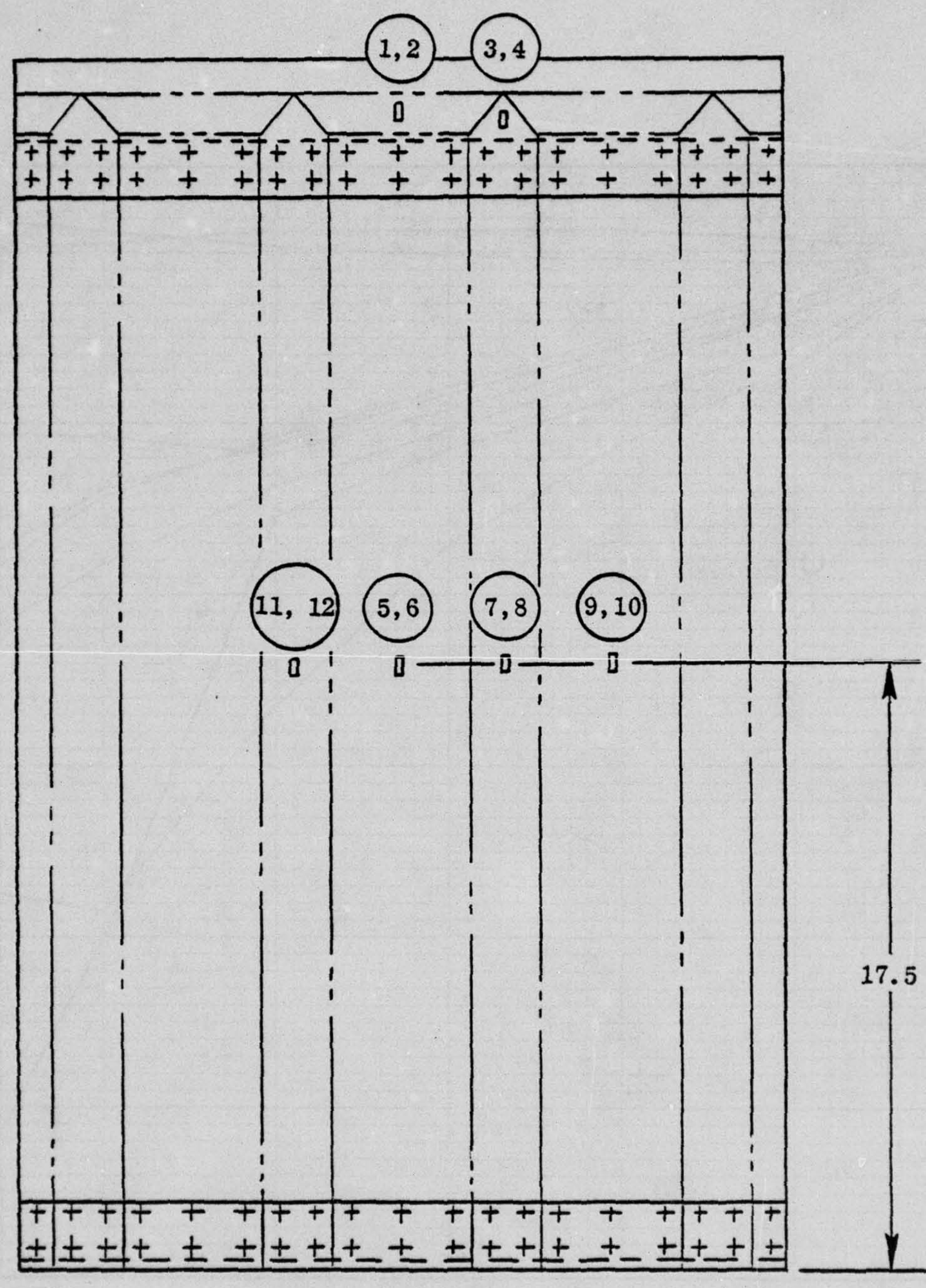


Figure 3.34. Corrugated Panel Load-Strain Curves



NOTES:

1. Install gages back-to-back within .06 in.
2. Gages 1 through 4 are Baldwin-Lima Hamilton (BLH) type FAE-25-12-S13.
3. Gages 5 through 12 are BLH type FAE-25-12-S1.

Figure 3.35. Corrugated Test Panel Instrumentation

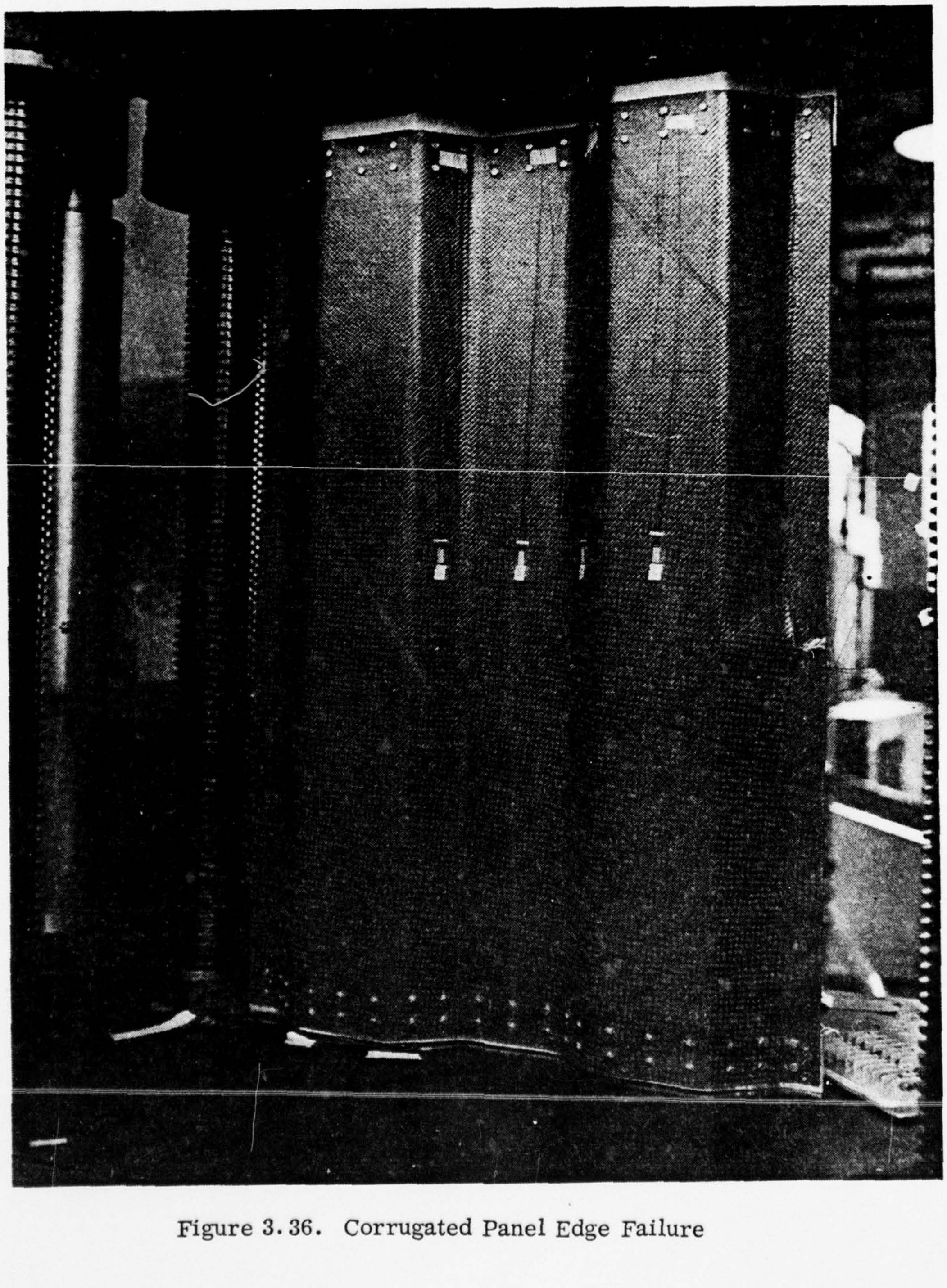


Figure 3.36. Corrugated Panel Edge Failure

TEST EQUIPMENT LIST

SUBELEMENT TESTS

Specimen Type	Test Equipment
Type I	Instron Universal Test Machine - Model TTD
Type II - Static Test	Instron 20,000# Tensile Test Machine - Model TTD
Type II - Fatigue Test	Sontagg SF-100 Universal Fatigue Test Machine
Type III & Type IV	Instron 20,000# Tensile Test Machine - Model TTD
Type V	Instron 20,000# Tensile Test Machine - Model TTD
Type VI & Type VII	Instron 20,000# Tensile Test Machine - Model TTD

FULL SIZE SUBCOMPONENT TESTS

Lower Cap Tension Joint	Tinius-Olsen 600,000# Test Machine Model Super L ESL 130297
Corrugated Panel - Deck Attachment Joint	Tinius-Olsen 200,000# Universal Test Machine

4

COMPOSITE TEST SECTION (CTS)

The composite test section phase of the program involved the structural design and analysis and manufacturing cost analysis of a 3-meter composite bridge test section.

4.1 COMPOSITE TEST SECTION DESIGN

The objective of the CTS design task was to generate a detailed design of a 3-meter lightweight bridge test section constructed of advanced composite materials. This section of the report discusses the design requirements established, the completed design configuration, and the CTS weight breakdown.

4.1.1 TEST SECTION DESIGN REQUIREMENTS. The design requirements for the composite bridge test section consist of geometrical constraints, ultimate strength, fatigue life, and environmental survivability. These requirements served as groundrules for the design of the composite test section.

Geometrical Constraints: The composite test section was designed to interface with existing metallic bridge ramp sections according to MERADCOM drawing number 13216E8001. The test section aluminum upper deck was to be 3 meters long and 60 inches wide with a bearing plate welded to each end to bear against the upper deck of the ramp sections. The lower tension caps of the test section were required to mate with existing fittings on the aluminum ramp sections. The overall height of the test section was required to be less than one meter.

Ultimate Strength: The composite test section was required to support a Military LoadClass (MLC) 60 vehicle at any point on its span in accordance with the "Trilateral Design and Test Code for Military Bridging and Gap Crossing Equipment." A static ultimate factor of safety of 1.50 was applied to all design loads.

Fatigue Life: The composite test section was required to sustain 15,000 MLC 60 vehicle crossings without failure. After this fatigue loading, the test section must meet the ultimate strength requirement.

Environmental Survivability: The composite test section must be capable of operating in a variety of environments ranging from tropical rain forests to arctic exposures. The major environmental requirements are listed below:

Temperature Range:	-65F to 160F
Moisture Exposure:	0% to 100% Relative Humidity
	Fresh, Salt, and Brackish Water

Battle Damage: 50 caliber projectile penetration

4.1.2 COMPOSITE TEST SECTION CONFIGURATION. The composite test section (CTS) configuration is illustrated in Figure 4.1. The design details are shown on Convair drawing number 72C0788 included in Appendix B. This structure was designed primarily to withstand the high bending moment induced by a Class 60 vehicle at mid-span. This high moment is reacted by a couple: tension in the lower caps and compression in the upper deck. A moderate shear load is reacted by four diagonal corrugated shear panels.

The four major components that make up the CTS are the upper deck treadway, the corrugated shear panels, the lower tension caps, and the end bulkheads.

Upper Deck Treadway: The upper deck treadway of the CTS is identical in cross section to that of the mating ramp sections. It is comprised of three 20-inch wide extruded aluminum sections that are welded together to form the total 60-inch width. Aluminum plates are welded to each end of the deck to provide a bearing surface that butts against the ramp section decks. The deck extrusion is made from 7005-T53 aluminum alloy that requires no heat treatment after welding.

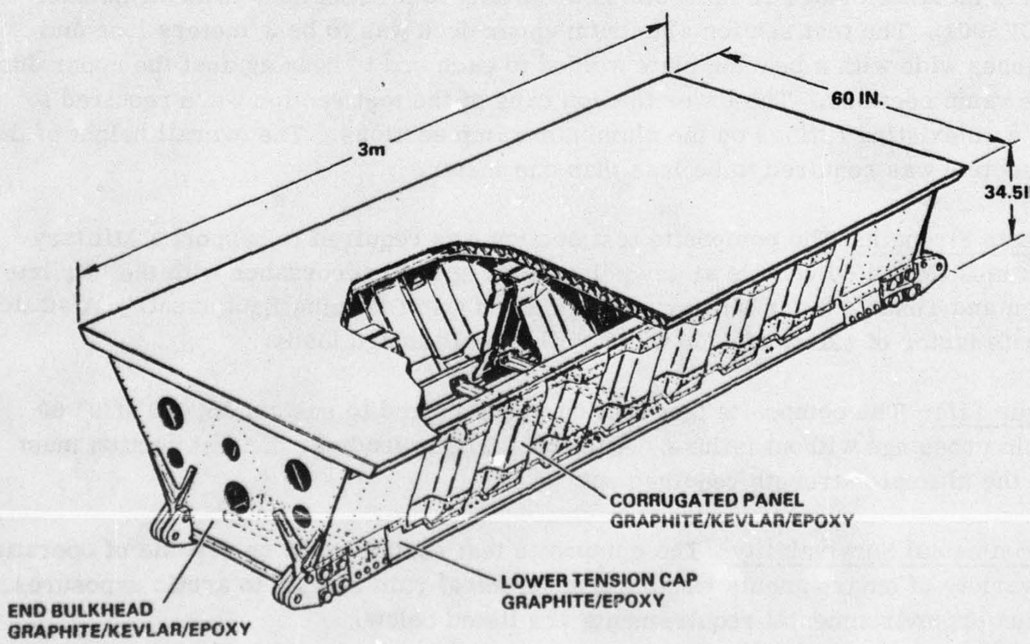


Figure 4.1. Composite Test Section Configuration

Corrugated Shear Panels: Four diagonal corrugated shear panels connect the upper deck with the tension caps. The corrugated shear panels are a hybrid composite laminate comprised of a graphite/epoxy (T300/934) core with Kevlar/epoxy facings. The overall laminate is 0.10 inch thick with 80% of the plies being graphite/epoxy. Each of the shear webs is 117 inches long and approximately 35 inches wide with corrugations in the center portions for stability against buckling. The shear panel are attached to the upper deck and lower tension caps by means of formed aluminum edge members as shown in Figure 4.2. The shear webs are riveted to the upper and lower edge members which are then welded to the upper deck and bolted to the lower tension cap. The ends of the shear webs, in the non-corrugated area, are stiffened with formed aluminum Z-section stiffeners that are riveted to the inside of each panel. The ends of the shear panels are attached to the end bulkheads with riveted aluminum angles.

Lower Tension Caps: The composite lower tension caps are rectangular section members (0.80 × 8.0 in.) made from T300/934 graphite/epoxy. The caps are attached to the lower edges of the corrugated shear panels using 1/4-inch huckbolts. The basic center section of the cap contains 60% longitudinal plies and 40% cross-plies at ±45 degrees. The ±45 plies are gradually dropped and replaced by 0.020-inch thick titanium interleaves at each end of the cap. Tapered graphite/epoxy doublers with additional titanium interleaves are bonded to both sides of the cap at each end for reinforcement. Stainless steel end fittings are bolted to the cap ends with four 1-1/4-inch diameter corrosion resistant steel bolts.

The lower tension cap is identical, except for overall length, to the tension cap development article that was successfully tested earlier in the program. Although the test section cap design could have been refined to reduce weight and cost, the higher reliability afforded by the original development article design was believed to be of greater importance.

End Bulkheads: The test section end bulkheads are trapezoidal shaped, 0.20-inch thick, flat laminates of graphite/epoxy with Kevlar/epoxy faces. The laminate contains 20% plies in the vertical direction with the remaining 80% at ±45 degrees. Large holes are cut through the bulkheads to permit access to the closed cells of the test section substructure. The bulkheads are attached to the shear panel ends using huckbolt fasteners.

4.1.3 CTS WEIGHT ANALYSIS. Detailed weight calculations were made for each part of the composite test section. The resulting weight breakdown is presented in Table 4-1. The weight target for the CTS exclusive of end attachment fittings was 125 Kg/m. The final composite design was 106 Kg/m without the steel fittings and only 125.7 including the fittings. For a 7-meter module of the same construction, the weight would equal only 103.3 Kg/m.

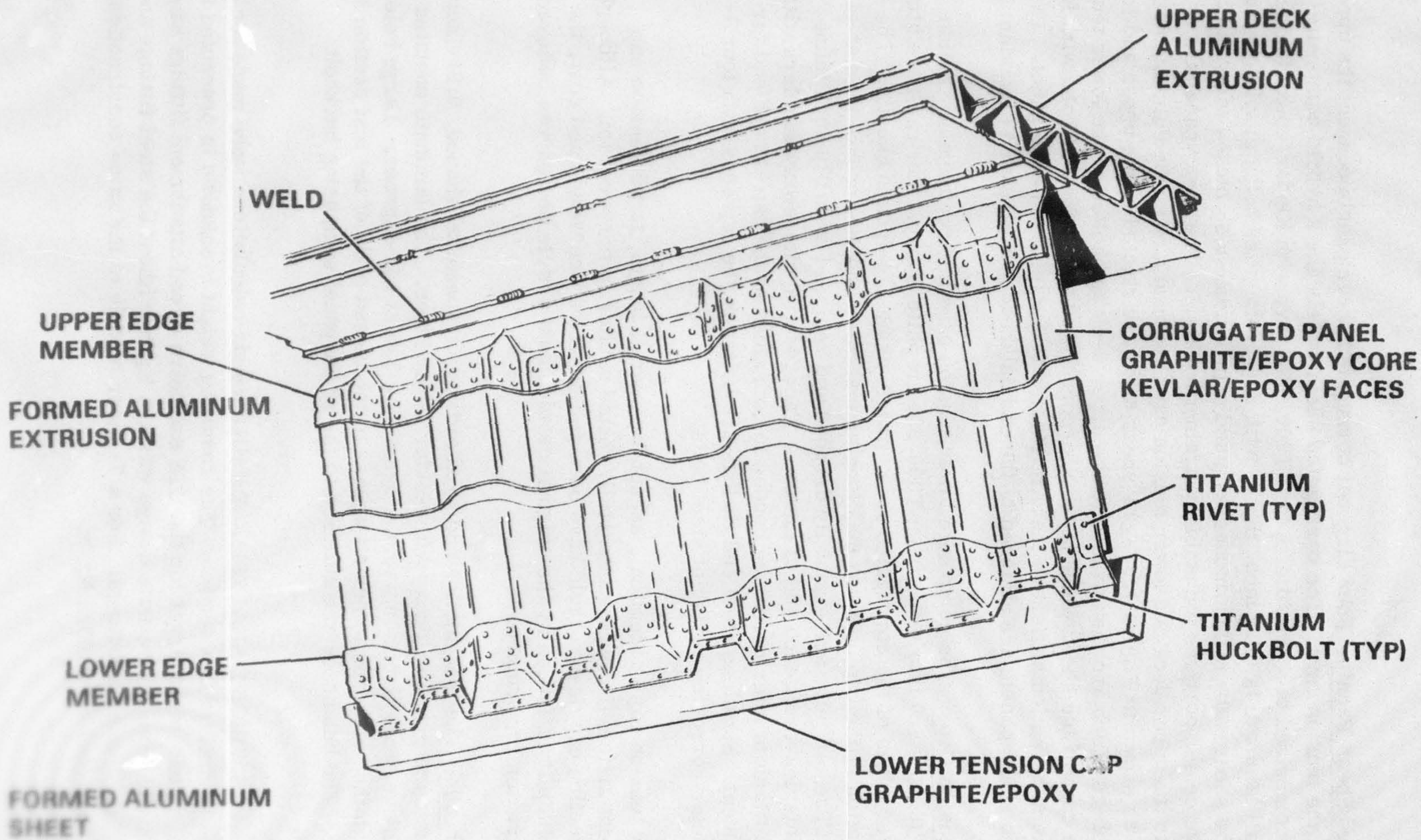


Figure 4.2. Corrugated Shear Panel Edge Attachment

AD-A046 949 GENERAL DYNAMICS/CONVAIR SAN DIEGO CALIF F/G 13/13
ADVANCED COMPOSITE ARMY ASSAULT BRIDGE DEVELOPMENT THROUGH SUBC--ETC(U)
JUN 77 DAAG53-76-C-0175
UNCLASSIFIED CASD-ASC-77-002 NL

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A046 949

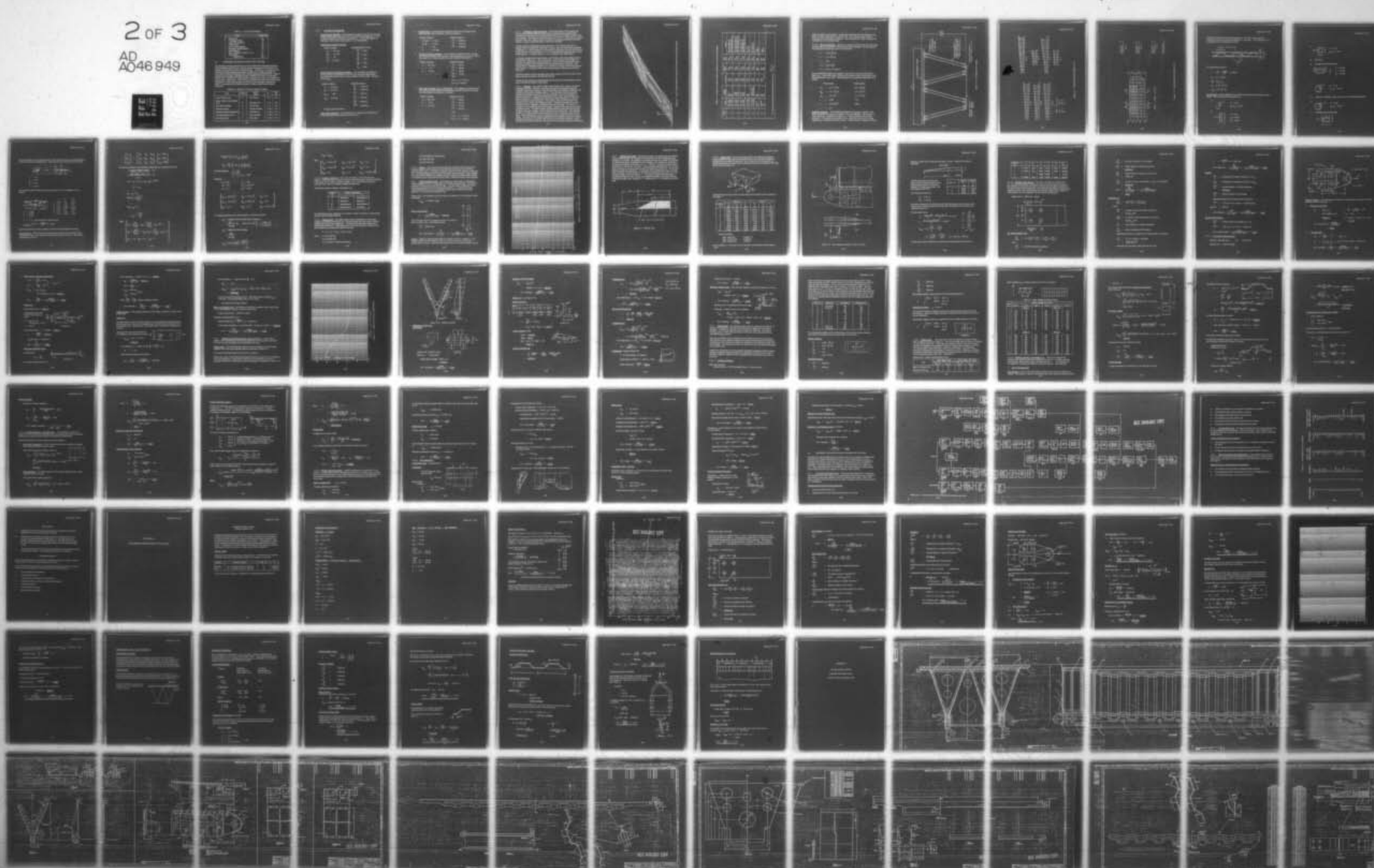


Table 4-1. CTS Weight Breakdown

Item	Weight (Kg)
Upper Deck	132
Corrugated Panels	47
Panel Edge Members	34
Tension Caps	51
Steel Tension Fittings	59
Aluminum Fittings/Angles	27
End Bulkheads	10
Misc. (fasteners, adhesive, etc.)	17
Total Weight	377
Weight/Meter	125.7

4.2 COMPOSITE TEST SECTION STRUCTURAL ANALYSIS

The structural analysis presented in this section details the mechanical properties used and analyses performed to verify the structural integrity of the Convair Test Section of the Armoured Vehicle Launched Bridge. The analysis is intended to show compliance with the Design Requirements specified in the Trilateral Design and Test Code for Military Bridging and Gap Crossing Equipment (Reference 2). Analysis methods and assumptions regarding boundary conditions and stress concentration factors used in stability and strength analyses throughout the report are considered to be accurate or conservative. This has been verified by the results of structural tests conducted on critical subcomponents all of which exceeded design requirements. Table 4-2 summarizes the minimum margins of safety obtained in the analyses performed.

Table 4-2. Summary of Minimum Margins of Safety

Item	Condition	Failure Mode	MS	Ref. Pg.
Lower Tension Cap	10	Net Tension	+0.15	4-21
Lower Tension Cap Interleaf Joint	10	Bolt Shear Out	+0.04	4-30
Steel Splice Fittings	10	Bolt Bearing	+1.28	4-33
Wishbone Fitting	9	Flange Crippling	+0.016	4-38
Wishbone Fitting Attachments	9	Bolt Bearing	+0.049	4-39
Corrugated Support Web	9	Plate Buckling	+0.075	4-45
Web Attachments	9	Rivet Shear	+0.026	4-53

4.2.1 MATERIAL PROPERTIES.

1. Graphite/Epoxy T300/934 — The mechanical properties used for the T300/934 graphite/epoxy system selected for the composite assault bridge are 'A' basis properties derived from data given in Reference 3 for the T300 fibers in conjunction with a similar epoxy system, i.e., Narmco 5208.

Unidirectional Lamina Properties

Elastic Constants	Allowable Strains μ in/in
E_{11} = 20.5 msi	ϵ_{11}^{tu} = 8400
E_{22} = 1.47 msi	ϵ_{11}^{cu} = 9200
μ_{12} = .30	ϵ_{22}^{tu} = 7000
G_{12} = 0.74 msi	ϵ_{22}^{cu} = 9200
	γ_{12} = 15000

Lower Tension Cap Laminate Properties — The mechanical properties of the lower tension cap laminate are derived from the above unidirectional lamina data using GD/Convair's laminate analysis program (SQ5). The layup is $(0_3/\pm45)_{NS}$.

Elastic Constants	Allowable Stresses
E_x = 13.25 msi	F_x^{tu} = 111000 psi
E_y = 3.2 msi	F_x^{cu} = 122000 psi
M_{xy} = .694	F_y^{tu} = 21200 psi
G_{xy} = 2.43 msi	F_y^{cu} = 27800 psi
	F_{xy}^{su} = 40900 psi
	F^{bru} = 110000 psi*

*based on data from Ref. 4

Support Web Laminates — The properties of the support web laminates are given along with the web analysis in Section 4.2.6.

2. **Kevlar/Epoxy — The mechanical properties used for the 181 Kevlar/epoxy fabric are taken from the Dupont "Kevlar Data Manual."**

Elastic Constants		Allowable Stresses	
E (warp)	= 4.0 msi	F^{tu}	= 73000 psi
E (fill)	= 4.0 msi	F^{cu}	= 21000 psi
μ	= 0.12	F^{su}	= 16000 psi
G	= 0.30 msi		

3. **Titanium Ti-6Al-4V Annealed — The mechanical properties for the .02 inch thick annealed titanium sheet material, used as interleaves in the lower tension cap joints, are 'A' basis properties from MIL-HDBK-5B Reference 5.**

Elastic Constants		Allowable Stresses	
E	= 16.0 msi	F^{tu}	= 134 ksi
μ	= .31	F^{ty}	= 126 ksi
G	= 6.2 msi	F^{cy}	= 132 ksi
		F^{su}	= 79 ksi
		F^{bru}	
		e/D = 1.5	= 171 ksi
		e/D = 2.0	= 208 ksi

4. **AISI 4340 Alloy Steel - H.T. = 200-210 ksi — The mechanical properties used for the AISI 4340 steel fitting are specification minimum (S) basis properties from MIL-HDBK-5B Reference 5 as follows:**

Elastic Constants		Allowable Stresses	
E	= 29.0 msi	F^{tu}	= 200 ksi
μ	= 0.32	F^{ty}	= 176 ksi
G	= 11.0 msi	F^{cy}	= 181 ksi
		F^{su}	= 120 ksi
		F^{bru}	
		e/D = 1.5	= 272 ksi
		e/D = 2.0	= 355 ksi

4.2.2 INTERNAL LOADS ANALYSIS. The internal loads in the composite test section of the assault bridge were determined by a finite element analysis which considered the existing 60 foot aluminum bridge with the 3M composite sections inserted at midspan. The analysis was conducted using GD/Convair's version of the computer program SOLID SAP, which is based on a family of programs developed by Professor Edward L. Wilson of the University of California at Berkeley.

Loading conditions considered included loading due to both the 60T tank and 70T wheeled vehicle combined with deadweight, braking, wind, and mud loads as specified in Reference 2. These loadings were considered in conjunction with zero and maximum eccentricity and zero and maximum (±1 in 10) longitudinal and transverse slopes at the bridge supports. A dynamic factor of 1.15 was applied to the vehicle loads.

A computer graphics display showing the overall bridge model and coordinate system is presented in Figure 4.3. Due to symmetry, only one quarter of the bridge was analyzed, the applied loads being separated into symmetric and antisymmetric parts and analyses performed for each part with appropriate boundary conditions. The results of these independent analyses were combined to give the correct total loads for each condition. A summary of the critical design loading conditions is presented in Table 4-3.

The finite elements used to represent these bridge members and the derivation of the input properties are given in the following sections.

Internal member loads are presented along with the analysis of the individual components in the analysis sections of the report.

4.2.2.1 Elements. The assault bridge model employs three types of elements: membranes, beams, and plates. Membrane elements include quadrilateral and triangular plane stress elements of specified thickness and arbitrary orientation with respect to the 3D global coordinate system. The membrane element possesses temperature dependent orthotropic material properties and has the capability to transmit uniformly or nonuniformly distributed surface loads, loads resulting from thermal strain due to a bilinear temperature field, loads resulting from a gravity field, and uniform surface pressure. The computer output for this element type includes normal, shear, and principal stresses. Membrane elements were used to simulate the webs, bulkheads, and bottom surface of the bridge. The beam is a constant cross-sectional element with arbitrary orientation with respect to the global coordinate system. The beam element includes uniformly distributed gravity loads, constant temperature changes, and the capability of pin ended joints. The computer results for the beam element are three forces and three moments at each end of the beam. Beam elements were used to simulate the truss arrangement of the assault bridge. The plate element includes quadrilateral and triangular elements of specified thickness and arbitrary orientation with respect to the 3D global coordinate system. The plate element has anisotropic material properties (separate bending and membrane),

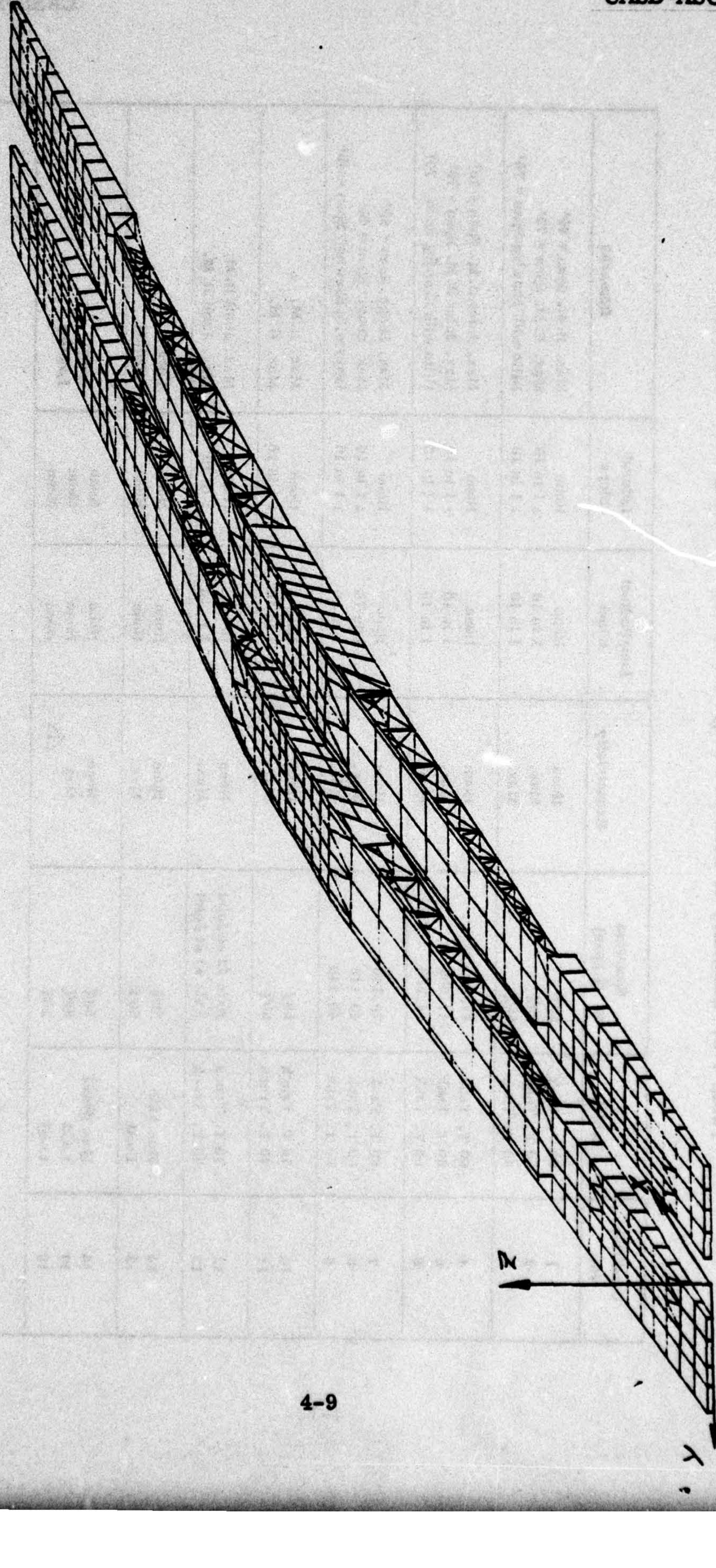
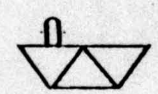


Figure 4.3. Army Assault Bridge with Composite Test Section–Finite Element Model

Table 4-3. Summary of Critical Design Conditions for Army Assault Bridge

Condition No.	Vehicle	Spanwise cg (% Span)	Eccentricity	Longitudinal Slope	Lateral Slope	Remarks
1	60 T. Tank	50%	None	None	None	Max. B.M. Span = 70'
2	60 T. Tank	50%	Max.	1 in 10	± 1 in 10	Max. B.M. Span = 70'
3	60 T. Tank	50%	Max.	1 in 10	± 1 in 10	Ditto with Skewing Span = 70'
4	60 T. Tank	44.286	None	None	None	Max. Joint B.M. Span = 70'
5	60 T. Tank	44.286	Max.	1 in 10	± 1 in 10	Max. Joint B.M. Span = 70'
6	60 T. Tank	44.286	Max.	1 in 10	± 1 in 10	Ditto with Skewing Span = 70'
7	60 T. Tank	40.148	None	None	None	Max. Shear Span = 40'
8	60 T. Tank	40.148	Max.	1 in 10	± 1 in 10	Max. Shear Span = 40'
9	60 T. Tank	40.148	Max.	1 in 10	± 1 in 10	Ditto with Skewing Span = 40'
10	70 T. Truck	50%	None	None	None	Max. B.M.
11	70 T. Truck	50%	Max.	1 in 10	± 1 in 10	Max. B.M.
12	70 T. Truck	Axle #3 at Joint	None	None	None	Max. Joint B.M.
13	70 T. Truck	Axle #3 at Joint	Max.	1 in 10	1 in 10	Max. Joint B.M.
14	Max Axle	50%	None	None	None	Local
15	Load	50%	Max.	None	None	Loading
16	Max Wheel	50%	None	None	None	Local
17	Load	50%	Max △1	None	None	Loading
18	Load	50%		None	None	

△1 Apply maximum wheel load midway between support ribs as shown.



uniform pressure load capability, temperature gradient through the thickness capability, and loads resulting from a gravity field. The computer output includes membrane and bending stress resultants. Plate elements were used to simulate the deck extrusion of the assault bridge.

4.2.2.2 Element Properties. Basically all members of the aluminum section of the assault bridge were made from 7000 series aluminum; therefore, for this analysis, the following properties were used for all elements:

$E = 10.5 \times 10^6$ psi

$G = 4.0 \times 10^6$ psi

$\mu = 0.33$

$w = 0.101$ lb/in^3

$\alpha = 13.0 \times 10^{-6}$ in/in°F

The composite test section was modeled to represent the structure illustrated in Figure 4.4. That is this section consists of an aluminum deck, Kevlar/epoxy webs, and graphite/epoxy lower caps. The properties for the composite materials are as follows:

		Kevlar/Epoxy	Graphite/Epoxy
E_{11}	=	4.5×10^6 psi	18.0×10^6 psi
E_{22}	=	4.5×10^6 psi	1.5×10^6 psi
G_{12}	=	0.3×10^6	0.6×10^6 psi
μ	=	0.125	0.32
w	=	0.048 lb/in^3	0.055
α	=	0.0	

Membrane Elements — The membrane elements for the aluminum section of the bridge represent the ramp lower surface, webs, and bulkheads. The location of these elements is illustrated in Figure 4.5. These elements used isotropic properties. The membrane elements for the composite section of the bridge employed the orthotropic properties option. These elements represent the shear

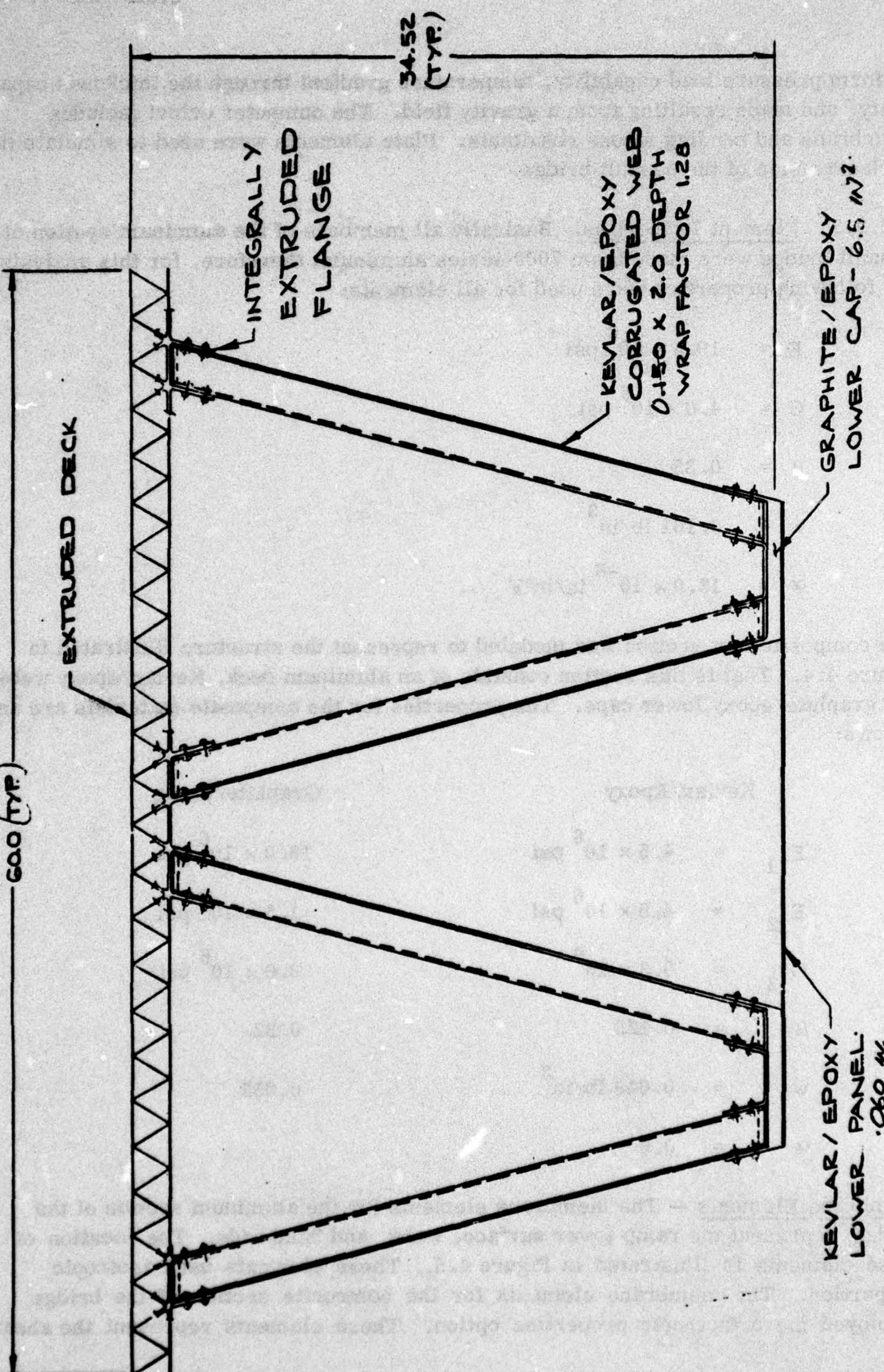


Figure 4.4. Corrugated Web Concept

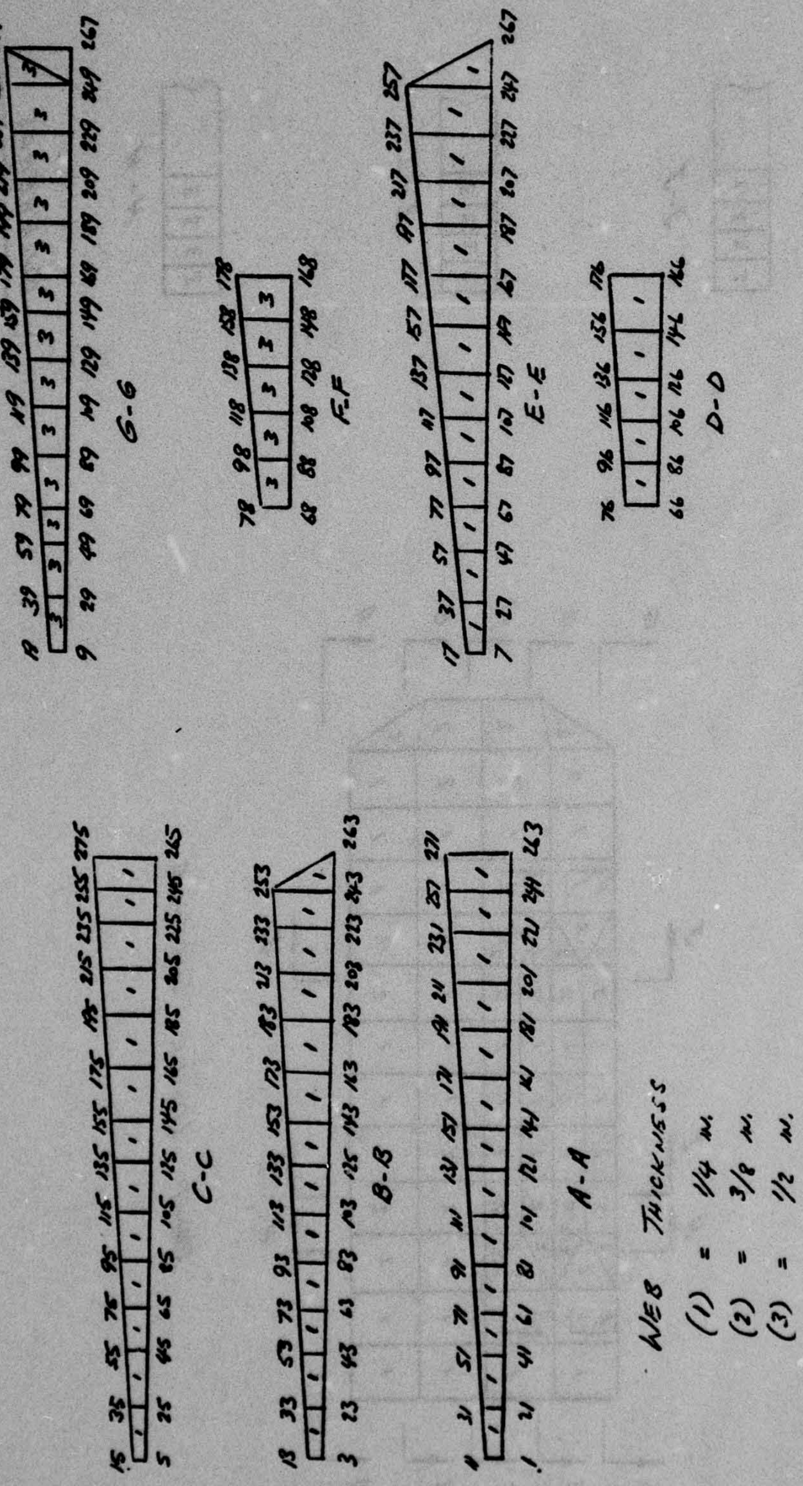


Figure 4.5. Membrane Elements (Sheet 1 of 2)

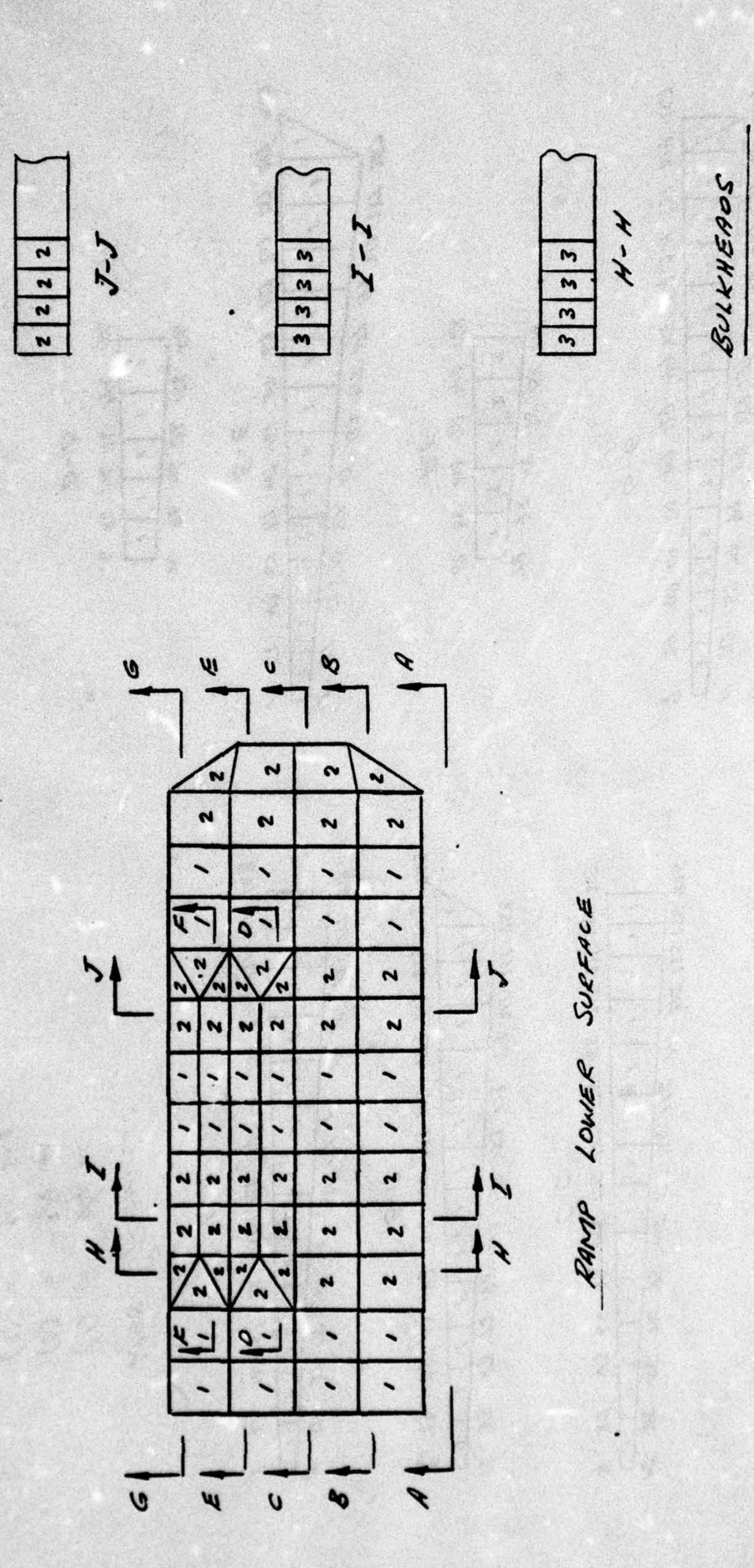
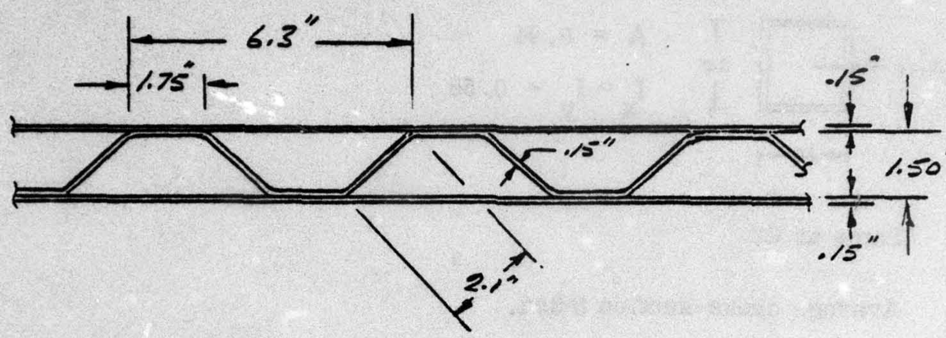


Figure 4.5. Membrane Elements (Sheet 2 of 2)

properties of the lower cap and corrugated web. The lower cap assumed the properties of Kevlar/epoxy whose thickness is 1.08 inches. The properties for the corrugated web were calculated as follows:



for pseudoisotropic layup —

$$t = \frac{A}{w} = \frac{3.045}{6.3} = 0.483 \text{ in.}$$

$$E_y = 4.5 \times 10^6 \text{ psi}$$

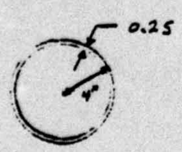
$$E_x t = E_y(t_1 + t_2)$$

$$E_x = 2.85 \times 10^6 \text{ psi}$$

$$G_{12} = 0.3 \times 10^6 \text{ psi}$$

Bar Elements — Several different cross-sections are used on the aluminum assault bridge. The cross-sectional properties are:

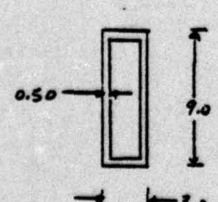
A.



$A = 6.09$

$I_x = I_y = 50.27$

B.

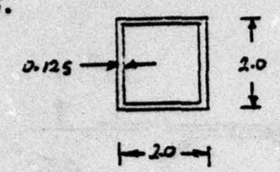


$A = 11.0$

$I_x = 96.92$

$I_y = 14.92$

C.

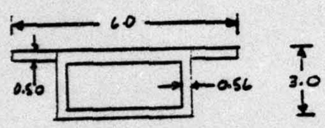


A = 0.94

$I_x = I_y = 0.55$

D. Same as C.

E. Average cross-section taken.

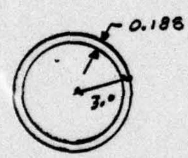


A = 10.966

$I_x = 13.383$

$I_y = 72.059$

F.

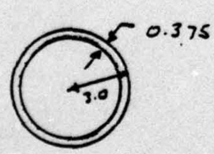


A = 3.43

$I_x = I_y = 15.90$

G. Same as F; however, area = Area x 0.75 to simulate hemispheres.

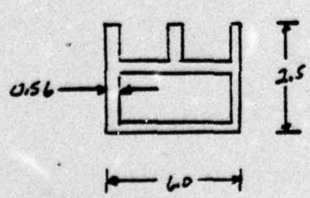
H.



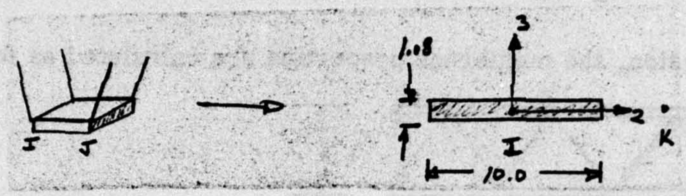
A = 6.63

$I_x = I_y = 31.81$

I. Average cross-section taken



The bar elements on the composite section of the bridge represent the bending stiffness of the lower cap and corrugated web. The properties of the lower cap are as follows:



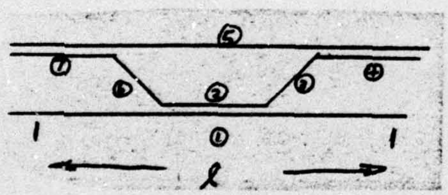
$A = 10.8$

$I_2 = 1.05$

$I_3 = 90.0$

$J = 91.05$

The properties which simulate the bending properties or the corrugated web is as follows:



	b	h	$\bar{y}$
1	0.15	6.3	3.15
2	0.15	1.75	3.15
3	2.1	0.15	0.8
4	0.15	0.875	0.437
5	0.15	6.3	3.15
6	2.1	0.15	4.8
7	0.15	0.875	5.425

$A = 3.045$

$I = 10.553$

$\bar{y} = 3.15$

$A = 0.01$ area included in membrane area

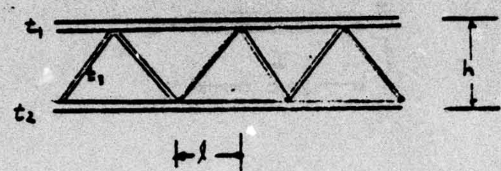
$$I_{effective} = \frac{I}{\ell} \times w = \frac{10.533}{6.3} \; 10 = 16.75$$

Material properties assume properties for Kevlar/epoxy pseudoisotropic layup.

Plate Elements — Plate elements simulate the deck extrusion of the assault bridge. As noted previously, both membrane and bending properties are input. The material relationship is given by:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{12} & G_{22} & G_{23} \\ G_{13} & G_{23} & G_{33} \end{bmatrix} \begin{Bmatrix} \epsilon_1 - \Delta T \alpha_1 \\ \epsilon_2 - \Delta T \alpha_2 \\ \gamma_{12} - \Delta T \alpha_3 \end{Bmatrix}$$

For the deck extrusion, the membrane properties are calculated as follows:



$$\text{Let } t = \bar{t}_x = \frac{1}{l}\left(t_1 l + t_2 l + t_3 (h^2 + l^2)^{1/2}\right)$$

$$\bar{t}_y = t_1 + t_2$$

$$\text{Let } E_x = 10^7$$

$$\text{Then } E_y = E_x \left(\frac{\bar{t}_y}{E_x}\right)$$

$$\text{Let } \mu_{xy} = .3$$

$$\mu_{yx} = \frac{.3\, E_y}{E_x}$$

Then

$$\begin{bmatrix} G_{11} = \dfrac{E_x}{1-\mu_x \mu_y}, \quad G_{12} = \dfrac{\mu_y E_x}{1-\mu_x \mu_y}, \quad G_{13} = 0.0 \\[2ex] G_{21} = \dfrac{\mu_x E_y}{1-\mu_x \mu_y} = G_{12}, \quad G_{22} = \dfrac{E_x}{1-\mu_x \mu_y}, \quad G_{23} = 0.0 \\[2ex] G_{31} = 0.0, \quad G_{32} = 0.0, \quad G_{33} = * \end{bmatrix}$$

$$*G_{33}\bar{t}_y = G\left(t_1 + t_2 + t_3 \frac{l}{(l^2 + h^2)^{1/2}}\right)$$

$$G_{33} = \frac{G}{\bar{t}_x}\left(t_1 + t_2 + t_3 \frac{l}{(l^2 + h^2)^{1/2}}\right)$$

For this extrusion $l = 1.25$

$h = 0.94$

$t_1 = t_2 = t_3 = 0.125$

Therefore

$\bar{t}_x = 0.41$	$\bar{t}_y = 0.25$
$E_x = 10^7$	$E_y = 6.2 \times 10^6$
$\mu_x = 0.3$	$\mu_y = 0.186$

$$\begin{bmatrix} G_{11} = 10.6 \times 10^7 & G_{12} = 1.97 \times 10^6 & G_{13} = 0.0 \\ G_{21} = 1.97 \times 10^6 & G_{22} = 6.57 \times 10^6 & G_{23} = 0.0 \\ G_{31} = 0.0 & G_{32} = 0.0 & G_{33} = 3.33 \times 10^6 \end{bmatrix}$$

For bending properties of the deck extrusion, calculate as follows:

D_{11} = Rigidity of the two plates plus corrugation

$$= \frac{Eh^3}{12(1-\mu_x^2)} + EI \quad \text{where } I = 0.5\, h^2 t \left[1 - \frac{0.81}{1 + 2.5(h/2l)^2}\right]$$

D_{22} = Rigidity of the two plates

$$= \frac{Eh^3}{12(1-\mu_x^2)}$$

$$D_{33} = 2(1/3)G\left[\left(\frac{h}{2}\right)^3 - \left(\frac{h-2t_1}{2}\right)^3\right]$$

$$D_{12} = \mu_x D_{11}$$

Thus:

$$\begin{bmatrix} D_{11} = 0.90 \times 10^6 & D_{12} = 0.27 \times 10^6 & D_{13} = 0.0 \\ D_{21} = 0.27 \times 10^6 & D_{22} = 0.8 \times 10^6 & D_{23} = 0.0 \\ D_{31} = 0.0 & D_{32} = 0.0 & D_{33} = 0.138 \times 10^6 \end{bmatrix}$$

4.2.2.3 Boundary Conditions. Since only one-quarter of the structure was modeled, it was necessary to impose symmetric and antisymmetric boundary conditions to the center lines to reflect the proper loading. For a model with two planes of symmetry there exist four boundary condition combinations.

The possible boundary condition combinations are:

Condition No.	Plane of Symmetry	
	1	2
I	Symmetric	Antisymmetric
II	Symmetric	Symmetric
III	Antisymmetric	Antisymmetric
IV	Antisymmetric	Symmetric

By combining these four conditions it is possible to reflect symmetric, antisymmetric, and asymmetric loading conditions.

4.2.2.4 Applied Loads. The design loads and load combinations for the assault bridge were evaluated according to the "Trilateral Design and Test Code for Military Bridging and Gap Crossing Equipment." The expected critical load conditions are summarized in Table 4-3. Added loads such as wind and mud will be combined with these conditions in computing the defined total load:

$$P = D + A_1 + 0.8A_2 + 0.6A_3 + 0.4A_4$$

where P is the total load

D is the dead load

A_1 is the tank or wheeled vehile load

A_2 is the braking or skewing load

A_3 is the wind load

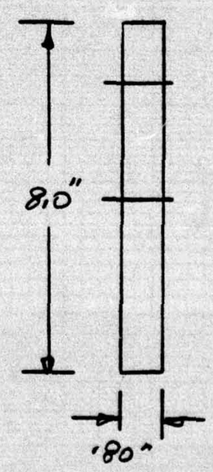
A_4 is the mud load

4.2.2.5 <u>Results.</u> The internal member loads from the finite element analysis are presented together with the analysis of the individual components in the following sections of this report. It should be noted that a number of minor changes in configuration, materials and gauges were made as the design study progressed. These changes were not reflected back into the computer model to update the internal loads; however, no significant error in the internal member loads is expected because of these changes.

4.2.3 <u>LOWER TENSION CAPS.</u> The bridge lower tension caps are rectangular section members (0.8 in × 8.0 in) made from T300/934 graphite/epoxy. The layup is comprised of 60% axial (0°) and 40% ±45° plies. The cap section is analyzed for the maximum axial tension from the finite element analysis. A conservative stress concentration factor (K_T) of 2.0 is applied to the net section stress at the small diameter (1/4 in) shear web attachment holes.

Design Load — The maximum cap load is given by Condition 10 (70 ton wheeled vehicle at midspan).

$$P_{max} = 198620 \text{ lb. limit}$$



<u>Stress on Net Section</u>

$$f_t = \frac{198620}{.80(8.0 - 2 \times .25)} = \underline{33103 \text{ psi}}$$

From laminate analysis the maximum strain in the axial (0°) fibers is 2435 μ in/in. The allowable strain

$$\epsilon_{11}^{tu} = 8400 \, \mu \text{ in/in.}$$

$$\therefore \quad \text{M.S. (net tension)} = \frac{\epsilon_{11}^{tu}}{1.5\,\epsilon_{11} K_t} - 1 = \frac{8400}{1.5 \times 2435 \times 2.0} - 1 = \underline{\underline{+0.15}}$$

<u>Fatigue</u> — Based on available fatigue data for notched [0/±45] G/E, Figure 4.6, the expected fatigue life under fatigue cycling at a net section stress of 33103 psi is greater than 10^7 cycles. Hence the basic tension cap is not considered fatigue critical.

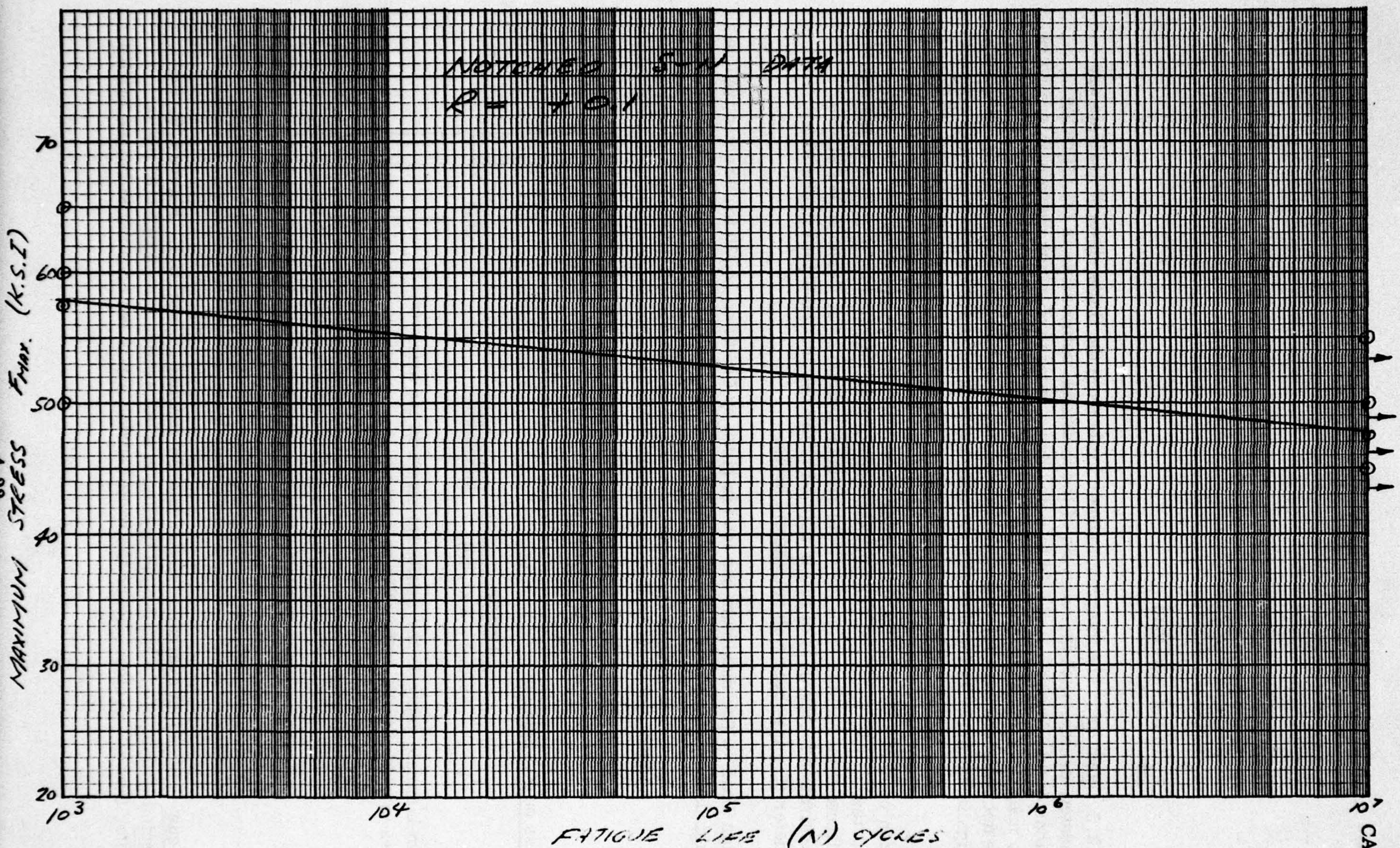


Figure 4.6. Axial Fatigue Properties of 6-Ply ⌊0 ±45⌋ G/E

4.2.4 <u>LOWER CAP JOINTS</u>. The basic cap section is reinforced by symmetrical 0.22 inch thick bonded on G/E doublers in the end joint area thus bringing the total thickness to 1.24 inch. The doublers are machine tapered over a length of 3.5 inches to minimize the stress concentration at the transition. The doublers are made from the same G/E material as the basic cap, i.e., T300/934. The layup is comprised of 54.5% axial (0°) and 45.5% × 45° plies. In the end fitting attachment area the .02 inch thick ±45° pairs in both the doublers and cap are deleted and replaced by .02 inch thick titanium (Ti-6Al-4V) interleaves. To minimize stress concentrations and to provide shear continuity, the interleaves are introduced in symmetrical pairs over a 3.0 inch transition length as shown in Figure 4.7. The analysis of the bolted attachment to the interleaf reinforcec cap is based on the method presented in the AFML Advanced Composites Design Guide, Reference 4. A fitting factor of 1.25 is applied in the joint area.

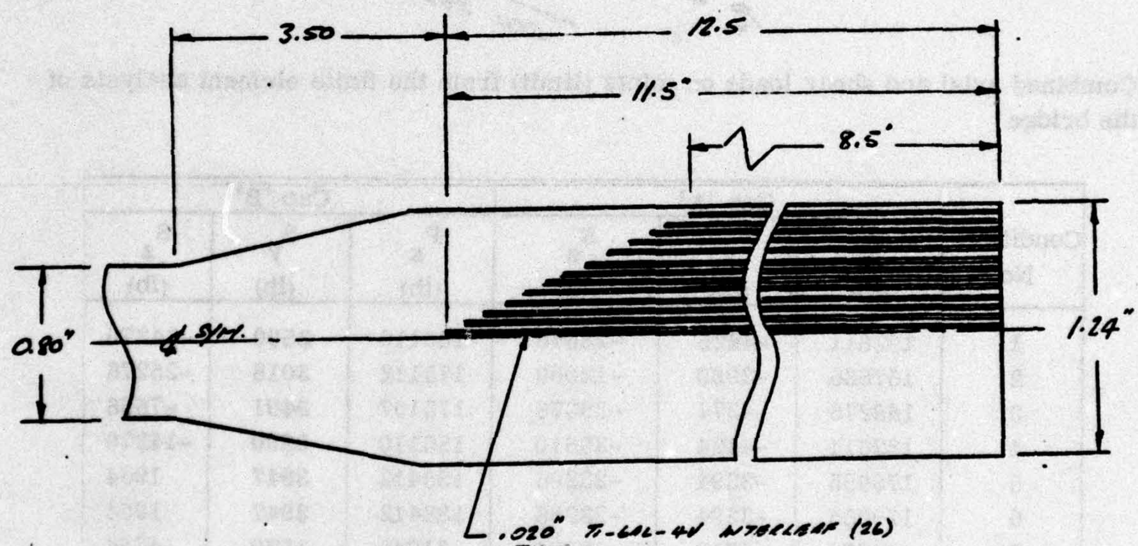
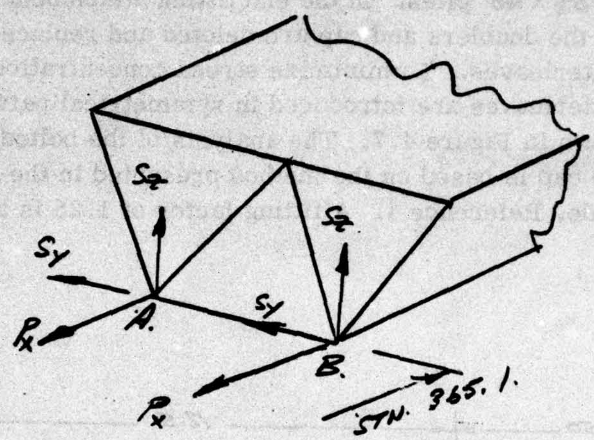


Figure 4.7. Interleaf Joint

4.2.4.1 Design Loads. The critical design loads on cap joints from the finite element analysis of the bridge are presented below for the maximum bending and maximum shear conditions respectively. Due to offsets of the end lug from the vertical and lateral cap supports local moments act on the joint in addition to the axial tension load (see Figure 4.8).



Combined axial and shear loads on joints (limit) from the finite element analysis of the bridge

Condition No.	Cap 'A' P_x (lb)	Cap 'A' S_y (lb)	Cap 'A' S_z (lb)	Cap 'B' P_x (lb)	Cap 'B' S_y (lb)	Cap 'B' S_z (lb)
1	182611	-4425	-23610	185110	3500	-14276
2	167636	-3990	-12000	175112	3018	-25276
3	168276	-4374	-29376	175107	3401	-7656
4	182611	-4424	-23610	185110	3500	-14276
5	179655	-3394	-23206	188412	3947	1964
6	179655	-3394	-23206	188412	3947	1964
7*	74870	-1513	17561	71642	1020	4784
8*	66143	-564	25983	70417	564	-5467
9*	68513	-1347	28143	81564	-234	-4287
10	194050	-3444	-17452	198395	4046	-4656
11	179655	-3394	-23206	188412	3947	1964

Critical Conditions

Max. axial load	Condition 10
Max. vertical load	Condition 3
Max. lateral load	Condition 1

*Note Conditions 7, 8 and 9 give rise to maximum vertical shear loads at Station 480.9.

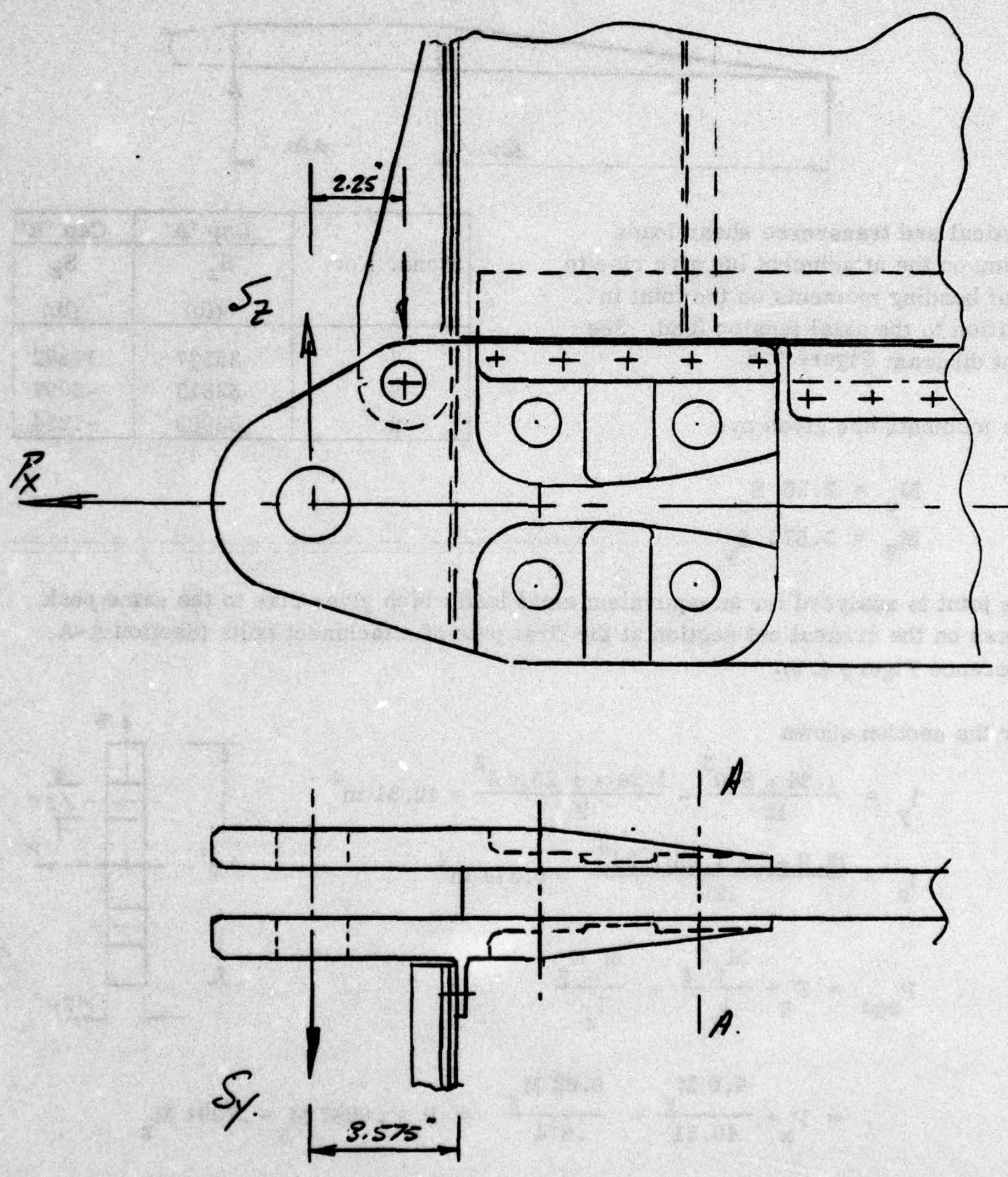
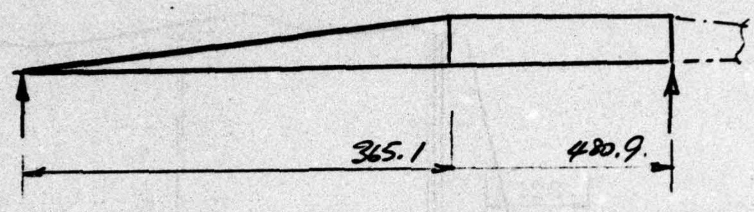


Figure 4.8. Local Moments Acting on Lower Cap Joints

Maximum vertical shear loads with end support at joint — Station 480.9 inch as illustrated.

(limit loads)



Vertical and transverse shear loads acting on the attachment lug give rise to local bending moments on the joint in addition to the axial tension load. See joint diagram Figure 4.8.

Cond. No.	Cap 'A' S_z (lb)	Cap 'B' S_z (lb)
7	35537	14862
8	52813	-5097
9	53083	-1284

The moments are given by:

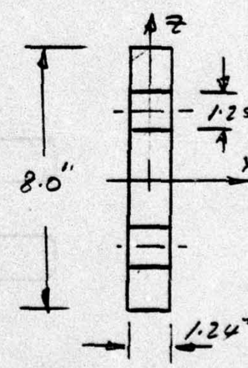
$$M_y = 2.25\ S_z$$
$$M_z = 3.575\ S_y$$

The joint is analyzed for an equivalent axial load which gives rise to the same peak stress on the critical net section at the first pair of attachment bolts (Section A-A, reference Figure 4.8).

For the section shown

$$I_y = \frac{1.24 \times 8.0^3}{12} - \frac{1.24 \times 1.25 \times 4^2}{2} = 40.51 \text{ in}^4$$

$$I_z = \frac{(8.0 - 2 \times 1.25)1.24^3}{12} = 0.874 \text{ in}^4$$



$$\therefore \quad P_{equ} = P_x + \frac{M_y C_z}{I_y} + \frac{M_z C_y}{I_z}$$

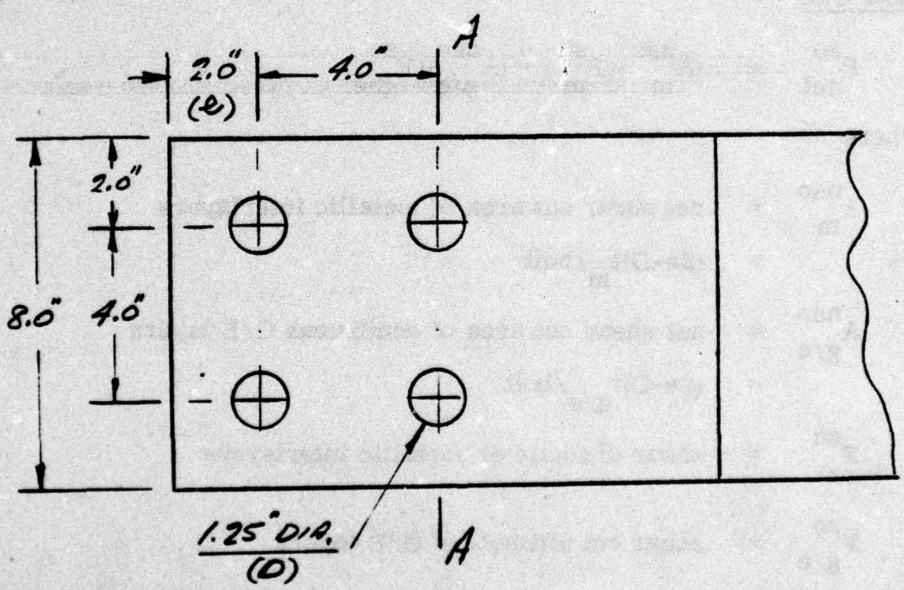
$$= P_x + \frac{4.0\ M_y}{40.51} + \frac{0.62\ M_z}{.874} = P_x + .0987\ M_y + .7094\ M_z$$

For the most critical conditions the end moments and equivalent axial loads are:

Condition No.	P_x	S_y	S_z	M_y	M_z	P_{eqv}
1	182611	-4425	23610	53122	15819	199076
3	168276	-4374	29376	66096	15637	185892
9	-	-	53083	119436	-	11788
10	198395	4046	4656	10476	14464	209690

4.2.4.2 Interleaf Joint Analysis. The lower cap ends are reinforced by 26 - .020 inch thick titanium interleaves in the joint area as shown in Figure 4.7. The interleaves replace the ±45° plies in the basic cap and reinforcing doublers leaving the axial (0°) plies continuous. The interleaf joint analysis is based on the method presented in the AFML Advanced Composites Design Guide, Reference 4. A fitting factor of 1.25 is applied to the cap loads in the joint area.

Design Load = 209700 lbs. (limit)



Net Tension (Section A-A)

$$P^{tu}_{net} = 0.4 \left[\left(A^{ns}_{m}\right)\left(F^{tu}_{m}\right) + \left(A^{ns}_{g/e}\right)\left(F^{tu}_{g/e}\right)\right]$$

where

A^{ns}_{m} = net area of metallic interlayers

$A^{ns}_{g/e}$ = net area of continuous G/E laminate

F^{tu}_{m} = tension ultimate of metallic interlayers

= 134000 psi

$F^{tu}_{g/e}$ = tension ultimate of continuous G/E layers

= 172200 psi

$$P^{tu}_{net} = 0.4\,[26 \times .02(8.0-2.5)(134000) + .88(8.0-2.5)(172200)]$$

$$= \underline{486675 \text{ lbs.}}$$

$$\therefore \quad M.S. = \frac{P^{tu}_{net}}{(U.F.)(K_f)P} - 1 = \frac{486675}{1.5 \times 1.25 \times 209700} - 1$$

$$= \underline{\underline{+0.24}}$$

Bolt Shear Out

$$P^{so}_{net} = (A^{nso}_{m})(F^{su}_{m}) + (A^{nso}_{g/e})(F^{so}_{g/e})$$

where

A^{nso}_{m} = net shear out area of metallic interlayers

= $(2e-D)t_m$/bolt

$A^{nso}_{g/e}$ = net shear out area of continuous G/E layers

= $(2e-D)t_{g/e}$/bolt

F^{su}_{m} = shear ultimate or metallic interlayers

$F^{so}_{g/e}$ = shear out ultimate of G/E layers

Neglecting the shear out strength of the unidirectional G/E material

$$P^{so}_{net} = (2 \times 2 - 1.25)(26 \times .02)(79000)$$

$$= \underline{112970 \text{ lbs}}\text{/bolt}$$

Assuming 55% of the load is carried by the end bolts:

$$P = \frac{209700}{4} \times 1.1 = 57667 \text{ lbs.}$$

$$\therefore \quad \text{M.S. (shear out)} = \frac{P^{so}_{net}}{(\text{U.F.})(K_f)P} - 1 = \frac{112970}{1.5 \times 1.25 \times 57667} - 1 = \underline{\underline{+0.04}}$$

Bearing

A^{br}_m = bearing area of metallic interlayers = $D \cdot t_m$

$A^{br}_{g/e}$ = bearing area of continuous G/E plies = $D \cdot t_{g/e}$

F^{bru}_m = bearing ultimate or metallic interlayers

= $\underline{197000 \text{ psi}}$

$F^{bru}_{g/e}$ = bearing ultimate of G/E laminate

Neglecting bearing on the unidirectional G/E layers

$$P^{bru} = 1.25 \times 26 \times .02 \times 197000 = 128050 \text{ lbs/bolt}$$

load/bolt = 57667 lb.

$$\therefore \quad \text{M.S. (bearing)} = \frac{P^{bru}}{(\text{U.F.})(K_f)P} - 1 = \frac{128050}{1.5 \times 1.25 \times 57667} - 1 = \underline{\underline{+0.18}}$$

Bearing Yield Analysis

F^{bry}_m = 171000 (Ti-6Al-4V annealed e/D = 1.5)

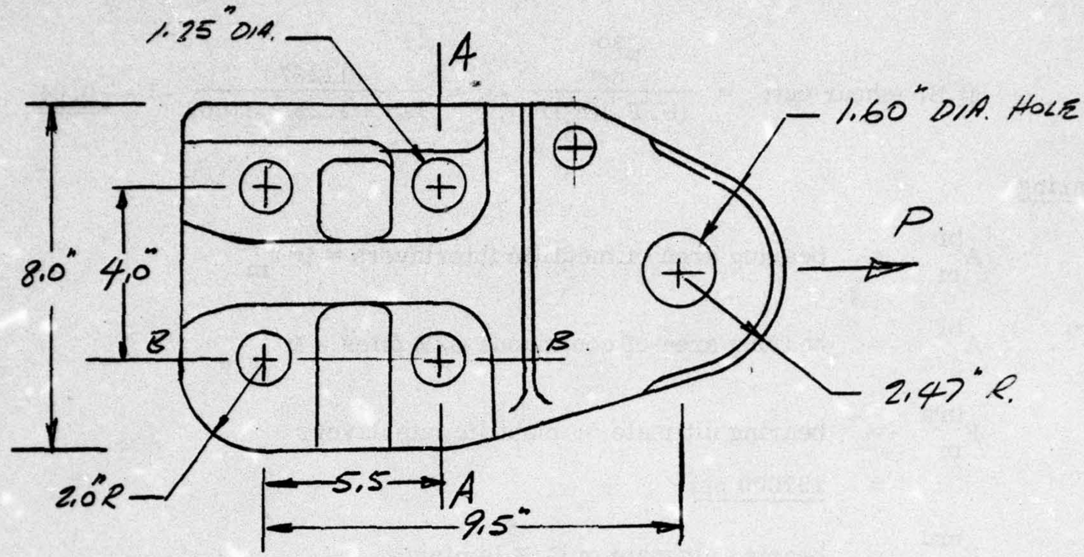
$$P^{bry} = 1.25 \times 26 \times .02 \times 171000 = 111150 \text{ lb.}$$

$$\text{M.S. (bearing yield)} = \frac{111150}{1.33 \times 1.25 \times 57667} - 1 = \underline{\underline{+0.16}}$$

4.2.4.3 Steel Splice Fitting Analysis.

Material: AISI 4340 steel H.T. = 200-210 ksi

Design Load = 104850 lb/fitting



End Lug Analysis — The lug analysis is based on the method given in the GD/Fort Worth Structures Manual (Reference 7).

1. **Tension on Net Section**

$$P_{tu} = K_t \cdot \sigma_{tu} \cdot A_t \qquad \lambda = \frac{D}{W} = \frac{1.75}{2 \times 2.47} = 0.35$$

$$= .88 \times 200000 \times 3.13 \qquad \therefore K_t = 0.88$$

$$= \underline{550880\ \text{lb.}} \qquad A_t = t(W-D) = .98(2 \times 2.47 - 1.75)$$

$$= \underline{3.13\ \text{in}^2}$$

$$\text{M.S. (net tension)} = \frac{550880}{1.5 \times 104850} - 1$$

$$= \underline{\underline{+2.50}}$$

2. **Lug Yield Load**

$$e/D = \frac{2.47}{1.75} = 1.41 \qquad \therefore K_{by} = 1.4$$

$$P_y = K_{by} \cdot A_{br} \cdot \sigma_{ty} = 1.4(1.75 \times .98) \times 175000 = 420175\ \text{lb.}$$

$$\text{M.S. (yielding)} = \frac{P_y}{1.33P} - 1 = \frac{420175}{1.33 \times 104850} - 1 = \underline{\underline{+2.01}}$$

3. **Shear Tearout, Bearing, Hoop Tension**

$$\left.\begin{aligned} e/D &= \frac{2.47}{1.6} = 1.54 \\ D/t &= \frac{1.6}{.98} = 1.63 \end{aligned}\right\} \therefore \ K_{br} = 1.5$$

$$P_{bru} = K_{br} \cdot \sigma_{tu} \cdot A_{br}$$

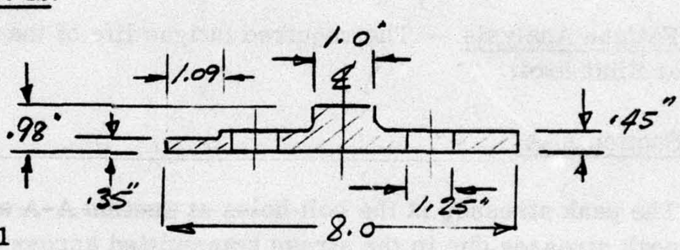
$$= 1.5 \times 200000(1.6 \times .98) = \underline{470400 \text{ lb.}}$$

$$\therefore \quad \text{M.S.} = \frac{P_{bru}}{1.5P} - 1 = \frac{470400}{1.5 \times 104850} - 1 = \underline{\underline{+1.99}}$$

Section A-A

Axial Tension Load = 104850 lb.

Considering the left hand portion of the section as shown



$$A = .45(4.0-1.15) + .5(.98-.45) - 1.09 \times .1$$

$$= 1.39 \text{ in}^2$$

Section A-A

Load on half section = .5 × 104850 = 52425 lb.

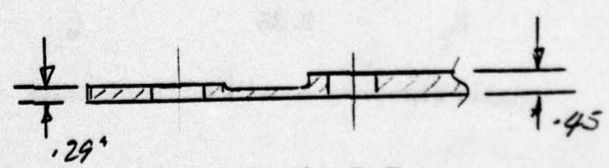
$$f_t = \frac{52425}{1.39} = \underline{37715 \text{ ksi}}$$

$$F_{tu} \text{(4340 steel)} = 200000 \text{ psi}$$

$$\therefore \quad \text{M.S.} = \frac{F_{tu}}{1.5 f_t} - 1 = \underline{\underline{+\text{High}}}$$

Bearing at Attachment Holes

Bearing Stress



$$= f_{br} = \frac{S}{Dt}$$

Section B-B

Assuming a peaking factor of 1.1

Max. Bolt Shear = 104850 × .25 × 1.1 = 28834 lb.

$$\therefore \quad f_{br} = \frac{28834}{1.25 \times .29} = \underline{79541 \text{ psi}}$$

$$e/D = \frac{2.0}{1.25} = 1.6$$

$$\therefore \quad \left.\begin{aligned} F_{bry} &= 255 \text{ ksi} \\ F_{bru} &= 272 \text{ ksi} \end{aligned}\right\} \text{Ref. 5}$$

Since $\frac{F_{bru}}{1.5} < \frac{F_{bry}}{1.33}$ ultimate bearing is critical

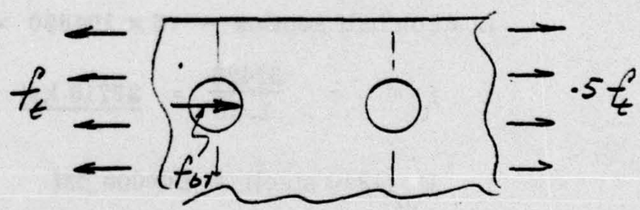
$$\therefore \quad \text{M.S. (bearing)} = \frac{F_{bru}}{1.5\, f_{br}} - 1 = \frac{272000}{1.5 \times 79541} - 1 = \underline{\underline{+1.28}}$$

Fatigue Analysis — The required fatigue life of the bridge components is 15000 cycles at limit load.

Section A-A

The peak stresses at the bolt holes at Section A-A are evaluated by superimposing the peak stresses due to the stress transmitted across the holes and the bearing stress at the attachment hole. Elastic stress concentration factors obtained from Reference 6 are used.

Assuming 50% of the load at Section A-A is transmitted to this second pair of bolts



$$\therefore \quad f_{trans} = .5\, ft = .5 \times 37715$$

$$= \underline{18857 \text{ psi}}$$

From Reference 6 Figure 69 with $\frac{D}{W} = \frac{1.25}{4} = .31$

$$K_t' = 2.35$$

Again assuming equal load on all bolts

$$f_{br} = \frac{P}{N.D.t} = \frac{104850}{4 \times 1.25 \times .45} = 46600 \text{ psi}$$

From Reference 6 Figure 83 with $\frac{D}{W} = 0.31$

$K_{be} = 1.54$

$$\therefore \quad f_{max} = f_{trans} \cdot K_t + f_{br} \cdot K_{br} = 18857 \times 2.35 + 46600 \times 1.54$$

$$= \underline{\underline{116078 \text{ psi}}}$$

From S-N curve for unnotched 200 HT - 4340 steel (Figure 4.9) with f_{max} = 116078 psi. The expected fatigue life (N) $> 10^7$ cycles

$\therefore$ The section is not fatigue critical.

<u>Bolts - End Fitting to Cap</u> — End fittings are attached to reinforce ends of gap by four 1-1/4 - inch diameter, 125 K.S.I. bolts in double shear.

Design Load on Joint = 209700 lb. (limit)

Assuming a peaking factor of 1.2

$$\text{Maximum Bolt Load} = \frac{209700}{4} \times 1.2 = 62910 \text{ lb.}$$

Double shear strength of 1 1/4 inch diameter, 125 ksi bolt = 92000 × 2 = $\underline{\underline{184000 \text{ lb.}}}$

$$\therefore \quad M.S. = \frac{S_{ult}}{(U.F.)(K_f)S} - 1 = \frac{184000}{1.5 \times 1.25 \times 62910} - 1 = \underline{\underline{+0.56}}$$

4.2.5 <u>WISHBONE FITTING ANALYSIS</u> - Material 7075-T73. These fittings located on the end bulkheads at each lower tension cap serve to transfer shear load from the lower cap end fittings into the adjoining shear webs.

<u>Design Loads</u> — The critical design loads are given by Condition 9 with the bridge supports at the end of the composite section as illustrated in Figure 4.8.

The design limit vertical shear at the end joint is 53083 lb.

Moment due to the 1.0-inch offset of the applied load from the face of the end bulkhead is assumed reacted by a concentrated couple load at the attachment pin and by a triangular distribution of bearing load on the fitting flange as illustrated in Figure 4.10.

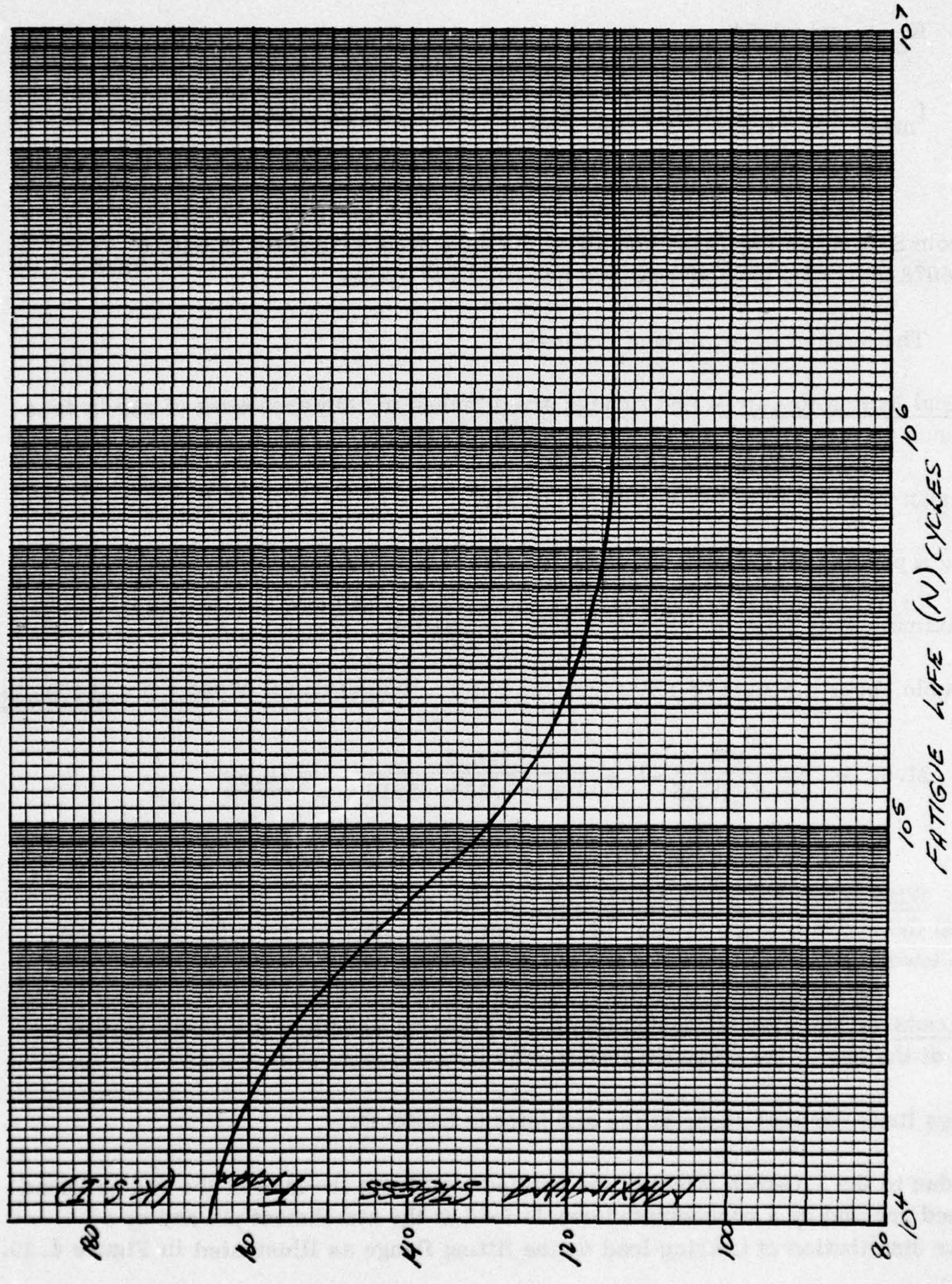


Figure 4.9. Fatigue S-N Curve for AISI 4340 Steel

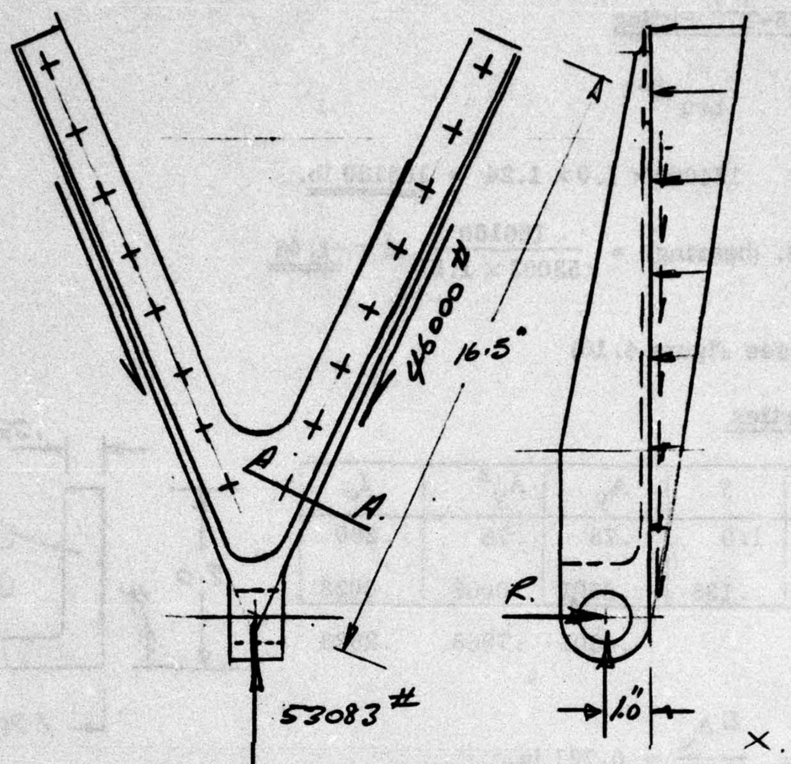
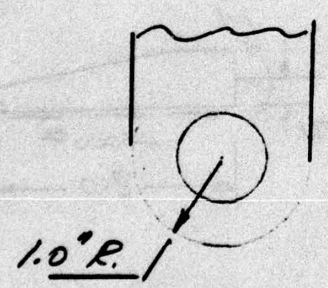
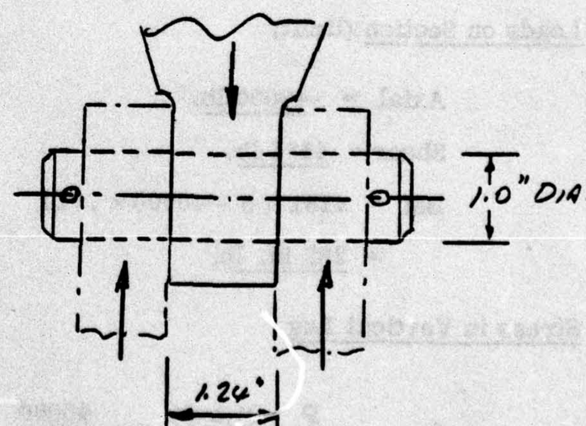


Figure 4.10. Wishbone Loading

Attachment to Lower Cap
End Fittings





Design Load = 53088 lb. limit

Shear Pin – 125 ksi steel

Double Shear Strength = 58900 × 2.0

= 117800 lb.

$$\therefore \quad \text{M.S. (pin shear)} = \frac{117800}{53083 \times 1.5} - 1 = \underline{\underline{+0.48}}$$

Bearing in 7075-T73 Fitting

$$P_{bru} = F_{bru} \cdot D \cdot t$$

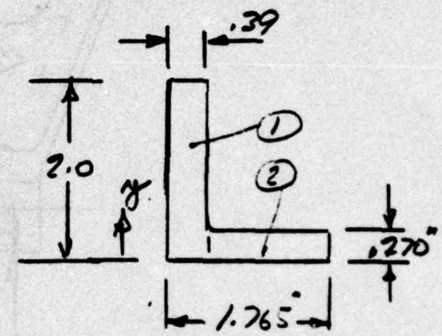
$$= 134000 \times 1.0 \times 1.24 = \underline{166160 \text{ lb.}}$$

$$\therefore \quad \text{M.S. (bearing)} = \frac{166160}{53083 \times 1.5} - 1 = \underline{\underline{+1.08}}$$

Section A-A (see Figure 4.10)

Section Properties

Item	A	y	A_y	A_y^2	I_o
1	.78	1.0	.78	.78	.260
2	.3713	.135	.0501	.0068	.0023
	1.1513		.8301	.7868	.2623



Section A-A

$$\bar{y} = \frac{\Sigma A_y}{\Sigma A} = 0.721 \text{ in.}$$

$$I = \Sigma A_y^2 + \Sigma I_o - \Sigma A_y \cdot \bar{y} = \underline{0.4506 \text{ in}^4}$$

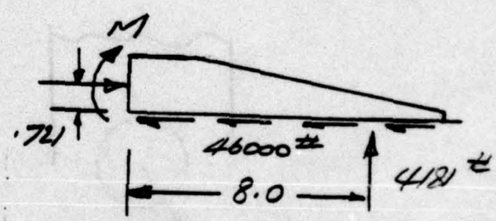
Loads on Section (limit)

Axial = $\underline{-46000 \text{ lb.}}$

Shear = $\underline{4181 \text{ lb.}}$

BM = $4181 \times 8 - 46000 \times .721$

= $\underline{282 \text{ in. lb.}}$



Stress in Vertical Leg

$$f = -\frac{P}{A} - \frac{M(h-\bar{y})}{I} = -\frac{46000}{1.1513} - \frac{282(2.0-.721)}{.4506}$$

$$= -\underline{40755 \text{ psi}}$$

Crippling Stress

For 7075-T73 Al

$F_{cy} = 54000$ psi

$E = 10.3 \times 10^6$ psi

$$F_{cc} = 0.57\, F_{cy}\left(\left(\frac{F_{cy}}{E}\right)^{1/2} \frac{b}{t}\right)^{-.81}$$

$$= 0.57 \times 54000\left(\left(\frac{54000}{10.3 \times 10^6}\right)^{1/2} \cdot \frac{1.865}{.39}\right)^{-.81}$$

$$= \underline{72670 \text{ psi}}$$

Use cutoff stress $= 1.15\, F_{cy} = 1.15 \times 54000 = \underline{62100 \text{ psi}}$

$$\therefore \text{ M.S.} = \frac{62100}{40755 \times 1.5} - 1 = \underline{\underline{+0.016}}$$

Stress in Horizontal Leg

$$f = -\frac{P}{A} + \frac{M\bar{y}}{I} = \frac{-46000}{1.1513} + \frac{282 \times .721}{.4506}$$

$$= \underline{-39503 \text{ psi}}$$

Crippling Stress

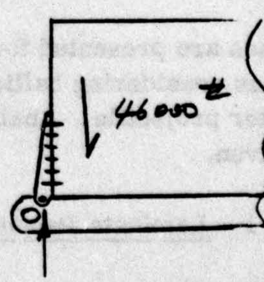
$$F_{cc} = .57\, F_{cy}\left(\left(\frac{F_{cy}}{E}\right)^{1/2} \frac{b}{t}\right)^{-.81}$$

$$= .57 \times 54000\left(\left(\frac{54000}{10.3 \times 10^6}\right)^{1/2} \frac{1.375}{.27}\right)^{-.81} = 69060 \text{ psi}$$

Use cutoff stress $= 1.15\, F_{cy} = 1.15 \times 54000 = \underline{62100 \text{ psi}}$

$$\therefore \quad \text{M.S.} = \frac{62100}{39503 \times 1.15} - 1 = \underline{\underline{+0.048}}$$

Attachments: Fitting to Beam Web



8 - 3/8 inch diameter Ti lockbolts

Design Shear Condition 9 = 46000 lb. (limit)

$$\text{Shear/Attachment} = \frac{46000}{8} = \underline{\underline{5750 \text{ lb.}}}$$

Single Shear Strength = 10490 lb.

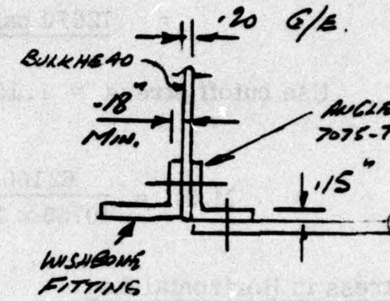
$$\therefore \quad \text{M.S. (shear)} = \frac{10490}{1.5 \times 5750} - 1 = \underline{+0.21}$$

Bearing in Fitting Flange — The minimum thickness of the tapered flange is 0.18 inch.

$$P_{bru} = F_{bru} \cdot D \cdot t$$

$$= 134000 \times .375 \times .18 = \underline{9045 \text{ lb.}}$$

$$\therefore \quad \text{M.S. (bearing} = \frac{9045}{5750 \times 1.5} - 1 = \underline{+0.049}$$



Bearing in G/E end bulkhead and 7075-T73 angle.

Neglecting .01 Kevlar faces on G/E bulkhead

$$P_{bru} = \Sigma\left(F_{bru} \cdot D \cdot t\right)$$

$$= 110,000 \times .375(.2 - .02) + 134000 \times .375 \times .15 = \underline{14962 \text{ lb.}}$$

$$\therefore \quad \text{M.S. (bearing)} = \frac{14962}{1.5 \times 5750} - 1 = \underline{+0.73}$$

4.2.6 SHEAR WEBS. The composite shear webs are comprised of a basic 0.10-inch thick corrugated web with flat reinforced end bays stabilized with aluminum stiffeners. The graphite material system considered is T300/934. The layup is $(0_2/\pm45_3)_s$ with .01-inch thick outer plies of 181 Kevlar cloth oriented at ±45° for increased damage tolerance.

The basic corrugated webs are analyzed for the maximum transverse compression edge load given by the maximum single wheel loading condition and for the maximum combined shear and transverse compression loads given by the maximum single wheel load condition. The reinforced end bays are analyzed for the local peak loads existing in the outboard webs.

Analyses are presented for local and general instability in addition to static strength analyses considering ballistic damage due to penetration of the web by a 0.5-inch diameter projectile. Analyses for the longitudinal and vertical shear web joints are also given.

4.2.6.1 Laminate Properties.

Basic Web Laminate

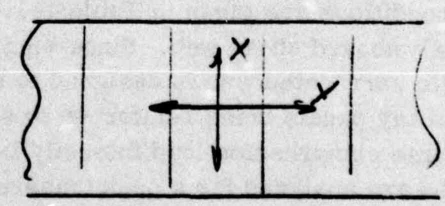
Material System: T300/734 graphite/epoxy, 181 Kevlar fabric.

The web laminate is designed to support transverse compression and shear loads, hence the laminate is made up from 0° plies for transverse strength and ±45° plies for shear strength and stiffness. Since the corrugated configuration makes the web ineffective for longitudinal loads, due to bending, no 90° plies are used. The G/E layup $(\pm 45_3/0_2)_s$, t = .08 inch, is comprised of 25% (0°) plies and 75% (±45°) plies. Outer plies of .01 inch 181 Kevlar at (45°) added for improved damage tolerance bring the overall thickness to 0.10 inch. The G/E laminate includes both .01 and .005 inch plies to provide a balanced symmetrical laminate of minimum weight and cost. The laminate ply stacking sequence designed to optimize the web buckling characteristics is as follows.

Ply No.	Material	Orientation	Thickness (in)
1	181 Kevlar	±45°	.01
2	T300/734	45°	.005
3		-45°	.005
4		-45°	.01
5		0°	.01
6		45°	.01
7		45°	.01
8		0°	.01
9		-45°	.01
10		-45°	.005
11	T300/734	45°	.005
12	181 Kevlar	∓45°	.01

The mechanical properties of the web laminate as derived from lamina properties using Convair's laminate analysis program (SQ5) are as follows.

Elastic Constants



$E_x = 5.965 \times 10^6$ psi

$E_y = 3.29 \times 10^6$ psi

$\mu_{xy} = 0.74$

$\mu_{yx} = 0.41$

$G = 3.69 \times 10^6$ psi

Allowable Stresses

$F_x^{tu} = 50120$ psi

$F_x^{cu} = 54890$ psi

F_y^{tu} = 23000 psi

F_y^{cu} = 32060 psi

F_{xy}^{su} = 51660 psi

The bending stiffness matrix required for web buckling analyses is:

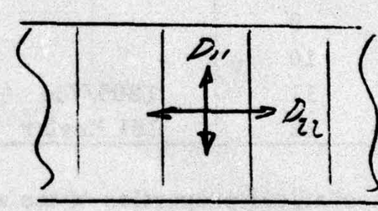
$$D = \begin{vmatrix} 447.9 & 272.3 & -40.7 \\ & 358.53 & -40.7 \\ & & 277.8 \end{vmatrix}$$

Reinforced End Bays t_w = 0.20 in.

The basic web laminate is doubled to provide the reinforcement required at the end bay locations. Hence the strength and elastic constants previously given for the basic web are applicable.

The bending stiffness matrix (D) required for the web buckling analysis is as follows:

$$D = \begin{vmatrix} 5166.5 & 2286.3 & -81.4 \\ & 3072.3 & -81.4 \\ & & 2401 \end{vmatrix}$$



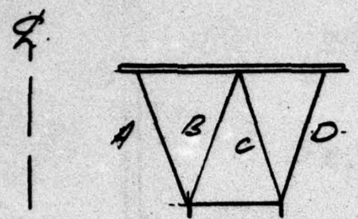
Orientation

4.2.6.2 Design Loads. **The shear loads in the web panels for the three critical shear conditions are given in Table 4-4. The critical design loads are given by Condition 9 in the outboard shear web. Since significant peaking is shown in the end bay panels, the basic corrugated web is designed to support a maximum shear loading of 800 lb/in. The end bay panels being reinforced to support the local peaks. The associated transverse compression load intensity is a uniform 411.0 lb/in. However, in addition the webs are analyzed for a peak transverse compression load of 525.0 lb/in. arising from the maximum single wheel load. (Condition 17)**

Support Webs: Design Loads Summary (limit)

Item	Max. Shear Cond.		Max. Trans. Ld. Cond.	
	Shear (N_{xy}) (lb/in)	Trans. Ld. (N_y) (lb/in)	Shear (N_{xy}) (lb/in)	Trans. Ld. (N_y) (lb/in)
Basic Corrugated Web	800	411	0.0	525
Reinforced End Bay	1400	411	0.0	525

Shear Loading (N_{xy}) in support panels for max shear conditions.



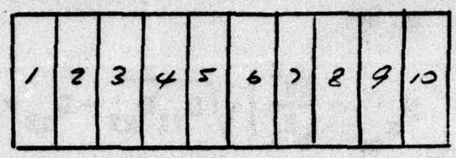


Table 4-4. Shear Loading in Support Panels

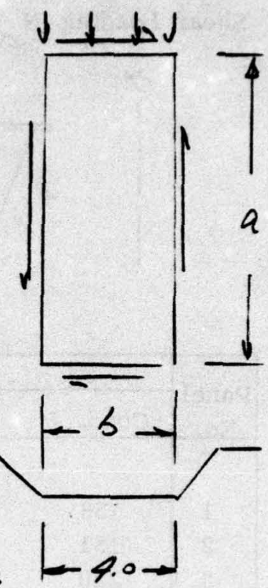
Panel No.	Shear Loading N_{xy} (lb/in)					
	Cond. 7	Cond. 8	Cond. 9	Cond. 7	Cond. 8	Cond. 9
		WEB 'A'			WEB 'B'	
1	156	62	62	198	96	141
2	181	34	23	254	256	289
3	220	79	46	282	276	309
4	249	105	68	314	302	335
5	271	121	84	347	327	360
6	283	128	93	361	346	379
7	286	124	92	357	347	374
8	281	104	79	350	339	373
9	263	54	41	343	336	369
10	289	73	48	343	152	226
		WEB 'C'			WEB 'D'	
1	342	417	446	399	546	621
2	239	196	219	308	413	498
3	272	229	252	351	442	536
4	303	258	281	381	480	576
5	336	284	308	412	533	630
6	351	305	330	432	569	664
7	349	310	334	441	575	667
8	346	310	332	460	609	695
9	319	266	286	500	691	767
10	475	574	566	807	1196	1360

4.2.6.3 Buckling Analysis — Corrugated Web. The web is analyzed for buckling under maximum transverse loading and for transverse loading combined with maximum shear; buckling of the individual plate elements comprising the web corrugations is considered in addition to column and general shear instability.

1. Basic Corrugated Web

Plate Buckling — The 4.0 inch wide plates forming the crown of the corrugation are critical. The analysis is made for an infinitely long simply supported orthotropic plate.

For $a/b = \infty$



The critical buckling load under <u>transverse compression</u> load is given by:

$$N_{x_{cr}} = \frac{2\pi^2}{b^2}\left\{\sqrt{D_{11}D_{22}} + D_{12} + 2D_{66}\right. \qquad \text{Ref. 3}$$

$$= \frac{2\pi^2}{4^2}\left\{\sqrt{447.92 \times 358.53} + 272.3 + 2 \times 277.76\right.$$

$$= 1515.7 \text{ lb/in}$$

<u>For Shear Loading</u>

$$N_{xy_{cr}} = \left(\frac{2}{b}\right)^2 \sqrt{D_{22}(D_{12} + 2D_{66})}\ \{11.7 + .532\theta + .938\theta^2\}$$

$$\text{where } \theta = \frac{\sqrt{D_{11}D_{22}}}{D_{12} + 2D_{66}} < 1.0 \ \Big\| \ \theta = \frac{(447.92 \times 358.53)^{1/2}}{272.3 + 2 \times 277.6} = 0.4843$$

$$N_{xy_{cr}} = \left(\frac{2}{4}\right)^2 \sqrt{358.53(272.3 + 2 \times 277.76)}\ \{11.7 + .532 \times 4843 + .938 \times 4843^2\}$$

$$= \underline{1659 \text{ psi}}$$

Maximum transverse compression loading

$$N_x = 525 \text{ lb/in}$$

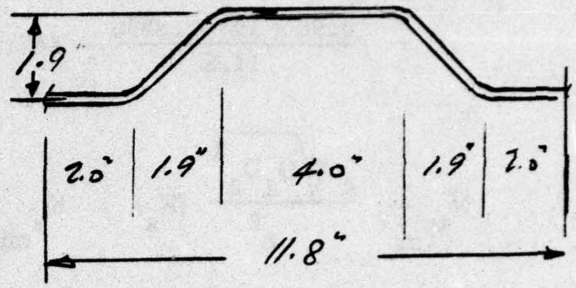
$$N_{xy} = 0.0$$

$$\therefore \quad M.S. = \frac{N_{x_{cr}}}{1.5\, N_x} - 1 = \frac{1515.7}{1.5 \times 525} - 1 = \underline{\underline{+0.92}}$$

<u>Column Buckling</u>

A single corrugation is considered as a pin ended Euler column.

Corrugation Section Properties



$$A = .10(8.0 + 2 \times 1.9 \times \sqrt{2})$$
$$= 1.34 \text{ in}^2$$

$$I = \frac{A_f h^2}{2} + \frac{b^1 h^3}{12}$$

$$= \frac{4.0 \times .1 \times 1.9^2}{2} + \frac{(2 \times .10 \sec 45°) \times 1.9^3}{12} = \underline{0.8836 \text{ in}^4}$$

$$P_e = \frac{\pi^2 EI}{\ell^2} = \frac{\pi^2 \times 5.96 \times 10^6 \times .8836}{34^2} = \underline{44691 \text{ lb.}}$$

Use plate buckling stress as cutoff.

$$P_e = N_{x_{cr}} \cdot S = 1515.7(8.0 + 2 \times 1.9 \times \sqrt{2}) = \underline{\underline{20270 \text{ lb.}}}$$

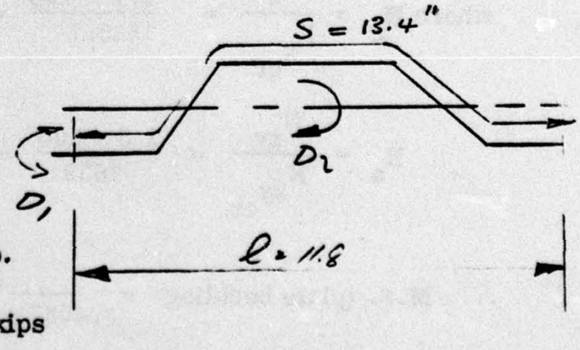
Max. transverse load/corrugation = 525 × 11.8 = 6195 lb.

$$\therefore \quad M.S. = \frac{20270}{6195} - 1 = \underline{\underline{+2.27}}$$

Web General Instability Under Shear Loading

Overall shear instability analysis is based on the method given in NASA TN D-242. Zero rotational restraint at the edges is assumed.

Longitudinal Bending Stiffness of Web (D_1)



$$= D_{22} \times \frac{\ell}{S}$$

$$= 358.53 \times \frac{11.8}{13.4} = 315.72 \text{ in. lb.}$$

$$= .31572 \text{ in. kips}$$

Transverse Bending Stiffness

$$(D_2) = \frac{E_x I}{\ell} + D_{11}$$

$$= \frac{5.96 \times 10^6 \times .8836}{11.8} + 447.92 = \underline{446740.8} \text{ in. lb.}$$

$$= \underline{446.7408} \text{ in. kips}$$

$$N_{xy_{cr}} = \frac{4\sqrt[4]{D_1 D_2^3}}{b^2} (K_s) \qquad K_{s_{min}} = 8.0$$

$$= \frac{(4\sqrt[4]{.31572 \times 446.7408^3})8.0}{34^2} = \underline{2.017 \text{ kips/in}}$$

$$= \underline{2017 \text{ lb/in}}$$

<u>Combined Shear and Compression Loading</u>

From Condition 9

N_{xy} = 800.0 lb/in
N_x = 411.0 lb/in limit

Plate Buckling Analysis — 4.0 inch wide plate

The M.S. for combined shear and compression is given by

$$M.S. = \frac{1}{R_c + R_s^2} - 1$$

$$\text{where } R_c = \frac{N_x}{N_{x_{cr}}} = \frac{411 \times 1.5}{1515.7} = 0.4067$$

$$R_s = \frac{N_{xy}}{N_{xy_{cr}}} = \frac{1.5 \times 800}{1659} = 0.7233$$

$$\therefore \quad M.S. \text{ (plate buckling)} = \frac{1}{.4067 + .7233^2} - 1 = \underline{\underline{+0.075}}$$

General Instability

Similarly for general instability

$$R_c = \frac{P}{P_e} = \frac{411.0 \times 1.5 \times 11.8}{20270} = .3589$$

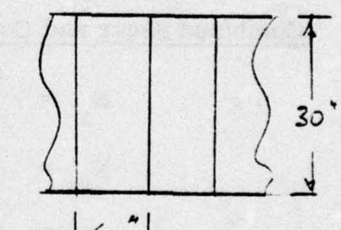
$$R_s = \frac{N_{xy}}{N_{xy_{cr}}} = \frac{800 \times 1.5}{2017} = .5949$$

$$\therefore \quad \text{M.S. (general instability)} = \frac{1}{.3589 + .5949^2} - 1 = \underline{\underline{+0.40}}$$

4.2.6.4 Buckling Analysis — End Bay Webs. The reinforced end bays are analyzed for local and general instability under the maximum transverse compression loading and for maximum shear combined with transverse compression.

Buckling of individual 6.0 inch wide panels between stiffeners

1. Transverse Compression — The 6.0 inch wide panels are analyzed as infinitely long, simply supported orthotropic plates.



The critical compression loading is given by:

$$N_{x_{cr}} = 2\frac{\pi^2}{b^2}\left\{\sqrt{D_{11}D_{22}} + D_{12} + 2D_{66}\right\} \quad \text{Ref. 4}$$

$$= \frac{2\pi^2}{6.0^2}\left\{\sqrt{5166.5 \times 3072.3} + 2286.3 + 2 \times 2401\right\}$$

$$= \underline{6071 \text{ lb/in}}$$

2. Shear Instability — The shear analysis is also made for infinitely long, simply supported orthotropic plates.

The critical shear loading is given by:

$$N_{xy_{cr}} = \left(\frac{2}{b}\right)^2 \sqrt{D_{22}(D_{12} + 2D_{66})}\ \{11.7 + .532\theta + .938\theta^2\}$$

$$\text{where} \quad \theta = \frac{\sqrt{D_{11}D_{22}}}{D_{12} + 2D_{66}} < 1.0$$

$$\theta = \frac{\sqrt{5166.5 \times 3072.3}}{2286.3 + 2 \times 2401} = 0.5621$$

$$\therefore \quad N_{xy_{cr}} = \left(\frac{2}{6}\right)^2 \sqrt{3072.3(2286.3 + 2 \times 2401)}\{11.7 + .5324 \times .5621 + .938 \times .5621^2\}$$

$$= \underline{6375.3}$$

Maximum Transverse Compression

$$N_x = 525 \text{ lb/in}$$

$$N_{xy} = 0.0$$

$$\therefore \quad M.S. = \frac{6071}{525 \times 1.5} - 1.0 = \underline{+HIGH}$$

Combined Shear and Compression

$$\left.\begin{aligned} N_x &= -411.0 \text{ lb/in} \\ N_{xy} &= 1400.0 \text{ lb/in} \end{aligned}\right\} \text{limit}$$

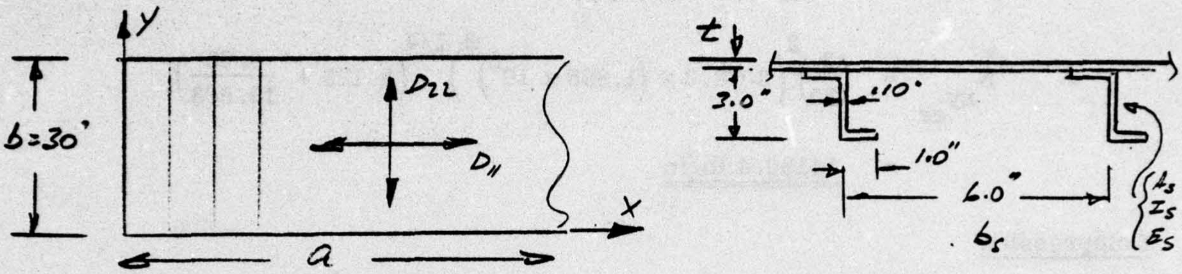
$$R_c = \frac{N_x}{N_{x_{cr}}} = \frac{1.5 \times 411}{6071} = .102$$

$$R_s = \frac{N_{xy}}{N_{xy_{cr}}} = \frac{1.5 \times 1400}{6375.3} = .33$$

$$M.S. = \frac{1}{.102 + .33^2} - 1 = \underline{\underline{+3.74}}$$

General Instability Analysis

The General Instability Analysis of the stiffened web are based on the method given in Reference 4. The web is conservatively analyzed as a long ($a/b = \infty$) simply supported orthotropic plate. The transverse bending rigidity of the web is increased to account for the bending rigidity of the web stiffener.



For the 0.2 inch thick reinforced web

$$\left.\begin{aligned} D_{11} &= 5166.5 \\ D_{22} &= 3072.3 \\ D_{12} &= 2286.3 \\ D_{66} &= 2401\ 0 \end{aligned}\right\}$$

In the buckling analysis D_{11} is defined in the 'X' direction as shown. For the web properties listed D_{11} is in the transverse direction. Hence D_{11} and D_{22} are exchanged in the analysis.

The overall bending rigidity D_{22} for the stiffened web is given by

$$D_{22} = D_{11} + \frac{E_w\left(b_s t(a)^2 + I_s\left(\frac{E_s}{E_w}\right) + A_s \frac{E_s}{E_w}(b)^2\right)}{b_s}$$

where a and b are the distances from the centroid of the skin and stiffener respectively to the centroid of the combined section.

$$D_{22} = 5766.5 + \frac{3.965 \times 10^6\left(6.0 \times .2(.654)^2 + .339\left(\frac{10.3}{5.965}\right) + .48\left(\frac{10.3}{5.965}\right)(.946)^2\right)}{6.0}$$

$$= \underline{1.835 \times 10^6}$$

Shear

$$N_{xy_{cr}} = \left(\frac{2}{b}\right)^2\left(D_{11}D_{22}^3\right)^{1/4}\left(8.125 + \frac{5.05}{\theta}\right)$$

where $\theta = \dfrac{\sqrt{D_{11}D_{22}}}{D_{12} + 2D_{66}} > 1.0$

$$= \frac{\sqrt{3072.3 \times 1.835 \times 10^6}}{2286.3 + 2 \times 2401} = 10.593$$

$$\therefore \quad N_{xy_{cr}} = \left(\frac{2}{30}\right)^2 \left(3072.3 \times \left(1.835 \times 10^6\right)^3\right)^{1/4} \left(8.125 + \frac{5.05}{10.593}\right)$$

$$= \underline{\underline{14190.4 \text{ lb/in}}}$$

<u>Compression</u>

Treating web as a plate column

$$N_{x_{cr}} = \frac{\pi^2 D}{6^2} = \frac{\pi^2 1.835 \times 10^6}{30^2} = \underline{20123 \text{ lb/in}}$$

For combined compression and shear, the margin of safety is given by:

$$M.S. = \frac{1}{R_c + R_s^2} - 1$$

$$R_c = \frac{411 \times 1.5}{20123} = .031 \qquad R_s = \frac{1400 \times 1.5}{14190.4} = .148$$

$$\therefore \quad M.S. = \frac{1}{.031 + .148^2} - 1 = \underline{\underline{+ \text{LARGE}}}$$

4.2.6.5 <u>Ballistic Damage Analysis</u>. Ballistic damage due to penetration of the web by a 0.5 inch caliber round is considered; peak strains at the edge of the resulting hole are computed assuming a stress concentration factor (K_t) of 3.0 in conjunction with the maximum lamina strains resulting from combined transverse compression and shear loads.

<u>Basic Corrugated Web</u> $\quad t_w = 0.10$ inch

Ultimate applied loads condition:

$$N_y = -616 \text{ lb/in}$$
$$N_{xy} = 1200 \text{ lb/in}$$

From laminate analysis program (SQ5) the maximum fiber strain is found in the plies at -45°

$$\epsilon_{max} = -.001852 \text{ in/in}$$

Allowable compression strain (ϵ_{11}) = -0.0092 in/in

$$\therefore \quad M.S. = \frac{.0092}{3 \times .001852} - 1 = \underline{\underline{+0.65}}$$

Reinforced End Bay $\quad t_w = 0.20$ **inch**

Ultimate applied loads condition:

$$N_y = 616.5 \text{ lb/in}$$

$$N_{xy} = 2100 \text{ lb/in}$$

From laminate analysis program (SQ5) the maximum fiber strain in the -45° lamina is:

$$\epsilon_{max} = -.001490 \text{ in/in}$$

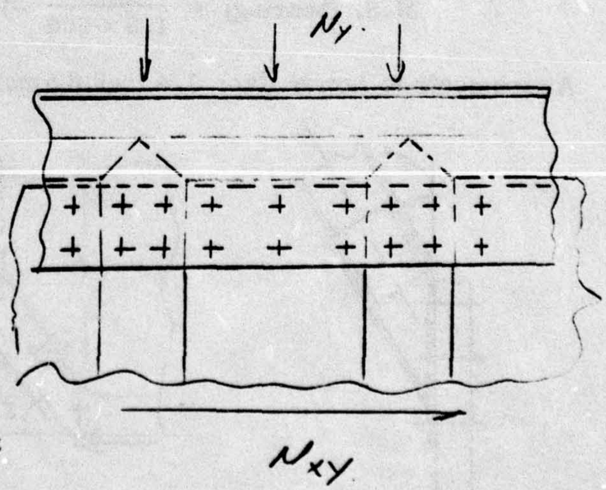
Allowable compression strain ($-\epsilon_{11}$) = -0.0092 in/in

$$\therefore \quad M.S. = \frac{.0092}{3 \times .001490} - 1 = \underline{\underline{+1.06}}$$

4.2.6.6 Web Attachments.

Longitudinal Joints: Corrugated Web

Attachments



3/16 inch diameter Cherry buck Ti rivets

$$F_{su} = 95.0 \text{ ksi}$$

Design Loads

Condition 9

$$\left.\begin{aligned} N_y &= 411.0 \text{ lb/in} \\ N_{xy} &= 800.0 \text{ lb/in} \end{aligned}\right\} \text{limit}$$

Attachments at 4.0 inch flat are critical.

Vertical Shear/Attachment $= 411 \times 4/6 = 274.0$ lb.

Horizontal Shear/Attachment $= 800.0 \times 4/6 = 533.3$ lb.

$$\text{Resultant Shear} = (274^2 + 549^2)^{1/2} = 600 \text{ lb.}$$

Single Shear Strength (95 ksi Ti Cherry Buck) = 2694 lb.

$$\therefore \quad \text{M.S. (rivet shear)} = \frac{2694}{1.5 \times 600} - 1 = \underline{+1.99}$$

Bearing strength in 0.16 inch 7005-T53 edge member

$$= D.t.F_{bru}$$

$$= .19 \times .16 \times 71800 \approx \underline{2183 \text{ lb.}}$$

Bearing strength in G/E web

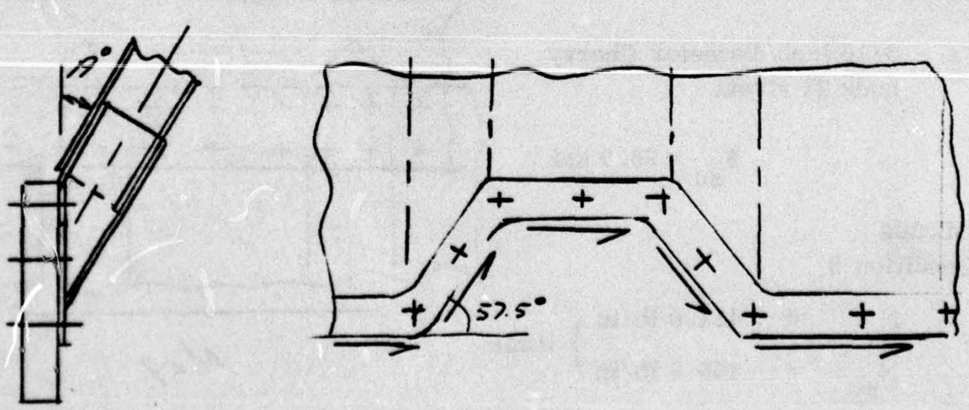
Neglecting outer .01 inch Kevlar plies, i.e., consider bearing in .080 inch $(0_2/\pm45_3)$ G/E only

$$P_{bru} = D.T.F_{bru}$$

$$= .19 \times .08 \times 110{,}000 = \underline{1672 \text{ lb.}}$$

$$\therefore \quad \text{M.S. (bearing)} = \frac{1672}{1.5 \times 600} - 1 = \underline{\underline{+0.85}}$$

Attachments to Lower Cap: 1/4 inch diameter Ti hucks at 1.5 inch spacing



Design Loads

$$N_y = 411.0 \text{ lb/in}$$

$$N_{xy} = 800.0 \text{ lb/in}$$

Vertical Load/Attachment = 411 cos(19°) × 1.5 = 583 lb.

Tangential Load/Attachment = 800 × 1.5 = 1200 lb.

Resultant Load/Attachment = $(583^2 + 1200^2)^{1/2}$ = 1334 lb.

Bearing Strength in $(0_3/\pm45)$ G/E cap

$$= F_{bru} D.t$$

$$= 110,000 \times .25 \times .25 = 6875 \text{ lb.}$$

$$\therefore \quad \text{M.S. (bearing)} = \frac{6875}{1.5 \times 1334} - 1 = +2.40$$

Single Shear Strength - 1/4 inch diameter 95 ksi shear Ti Huck

= 4660 lb.

$$\therefore \quad \text{M.S. (shear)} = \frac{4660}{1.5 \times 1334} - 1 = +1.3$$

Longitudinal Joints: End Bays

Attachments web to connector: two rows of 3/16 inch diameter Ti Cherry Buck rivets at 1.2 inch maximum spacing.

Design Loads

Condition 9

$$\left.\begin{array}{l} N_y = -411.0 \text{ lb/in} \\ N_{xy} = 1400.0 \text{ lb/in} \end{array}\right\} \text{limit}$$

Vertical Shear/Attachment = 411.0 × 1.2 = 493.2 lb.

Horizontal Shear/Attachment = 1400 × 1.2 = 1680 lb.

$S_r = (493.2^2 + 1680^2)^{1/2} = 1751$ lb.

Bearing Strength in G/E web = $D.t.F_{bru}$ = .19 × .16 × 110000 = 3344 lb.

Single Shear Strength (95 ksi shear Ti Cherry Buck) = 2694 lb.

$\therefore$ M.S. (rivet shear) = $\frac{2694}{1.5 \times 1751} - 1 = \underline{0.026}$

Attachments: Lower connector to G/E cap, 1/4 inch diameter Ti Huck bolts at 1.5 inch spacing

Vertical Shear/Attachment = 411 × 1.5 cos(A) = 583 lb.

Horizontal Shear/Attachment = 1400 × 1.5 = 2100 lb.

$S_r = (538^2 + 2100^2)^{1.2} = \underline{2179 \text{ lb.}}$

Single Shear Strength (1/4 inch diameter Ti Huck) = 4660 lb.

Bearing Strength in G/E cap

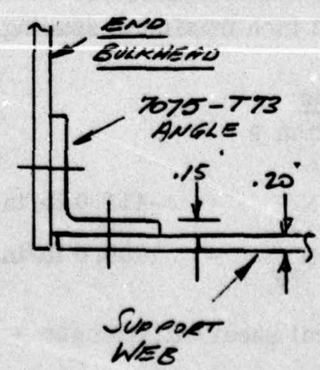
$= P_{bru} = D.t\ F_{bru}$ Since $t_{cap} > D$ use D^2

$= .25^2 \times 110000 = \underline{6875 \text{ lb.}}$

$\therefore$ M.S. (shear) = $\frac{4660}{1.5 \times 2179} - 1 = \underline{+0.42}$

Transverse Joints at End Bays

Attachment - A single row of 1/4 inch diameter Titanium lockbolts at 1.5 inch spacing.



Design Shear Loading

N_{xy} = 1400 lb/in (limit)

Load/Attachment = 1400 × 1.5
= 2100 lb.

Single Shear Strength 1/4 inch diameter Ti Lockbolt (F_{su} = 95 ksi)

= 4660 lb.

Bearing in .20 inch Composite Web

Neglecting the inner and outer Kevlar plies in the doubled end bay layup t_{eff} = .16 inch

$$P_{bru} = F_{bru}\,D.t = 110{,}000 \times .25 \times .16 = \underline{4400\text{ lb.}}$$

Bearing in 0.15 Attachment Angle (7075-T73)

$$P_{bru} = F_{bru}\,D.t = 134000 \times .25 \times .16 = \underline{5360\text{ lb.}}$$

$\therefore$ Bearing in the composite web is critical

$$\text{M.S. (bearing)} = \frac{P_{bru}}{1.5(S)} - 1$$

$$= \frac{4400}{1.5 \times 2100} - 1 = \underline{\underline{+0.40}}$$

4.3 COMPOSITE TEST SECTION MANUFACTURING COST ANALYSIS

The objective of the manufacturing cost analysis task was to establish a manufacturing sequence and to identify and estimate all items of cost in fabricating two 3-meter composite test sections conforming to Convair drawing number 72C0788 (Appendix B). Throughout the design process, the design was continually reviewed by composite fabrication and tooling experts who suggested ways of making the test section lower cost. These suggestions were incorporated into the design whenever possible without compromising the structural integrity or reliability of the structure.

4.3.1 CTS MANUFACTURING PLAN. Following design completion, a manufacturing sequence and flow plan (Figure 4.11) was prepared to identify the major manufacturing operations and tooling required to build the composite test section. Each of the major operations was then broken down into detail components which were then subjected to a cost analysis.

Manufacturing Ground Rules and Assumptions

1. Assume go-ahead 1 May 1977.
2. Manufacture two (2) test sections per Drawing No. 72C0788.

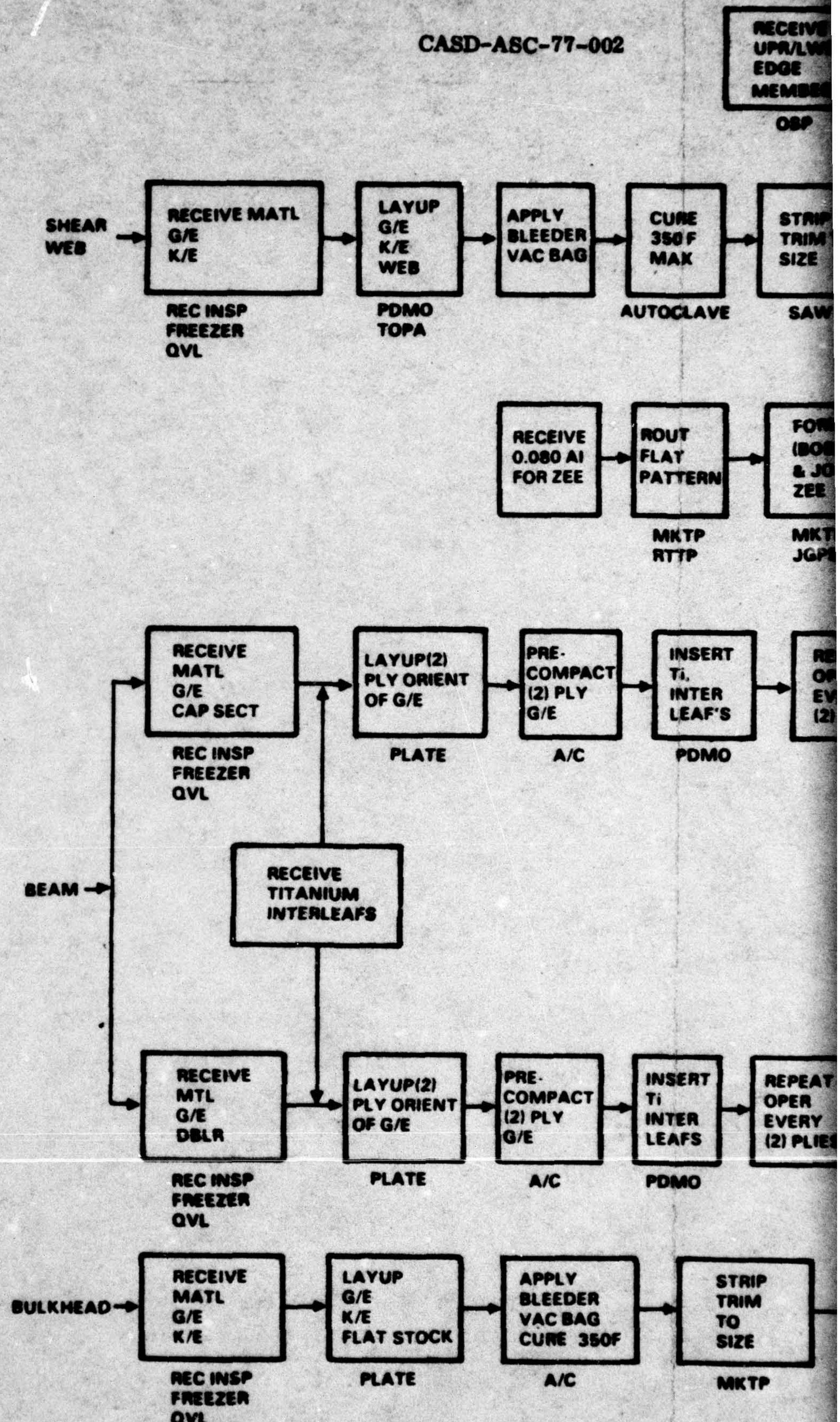
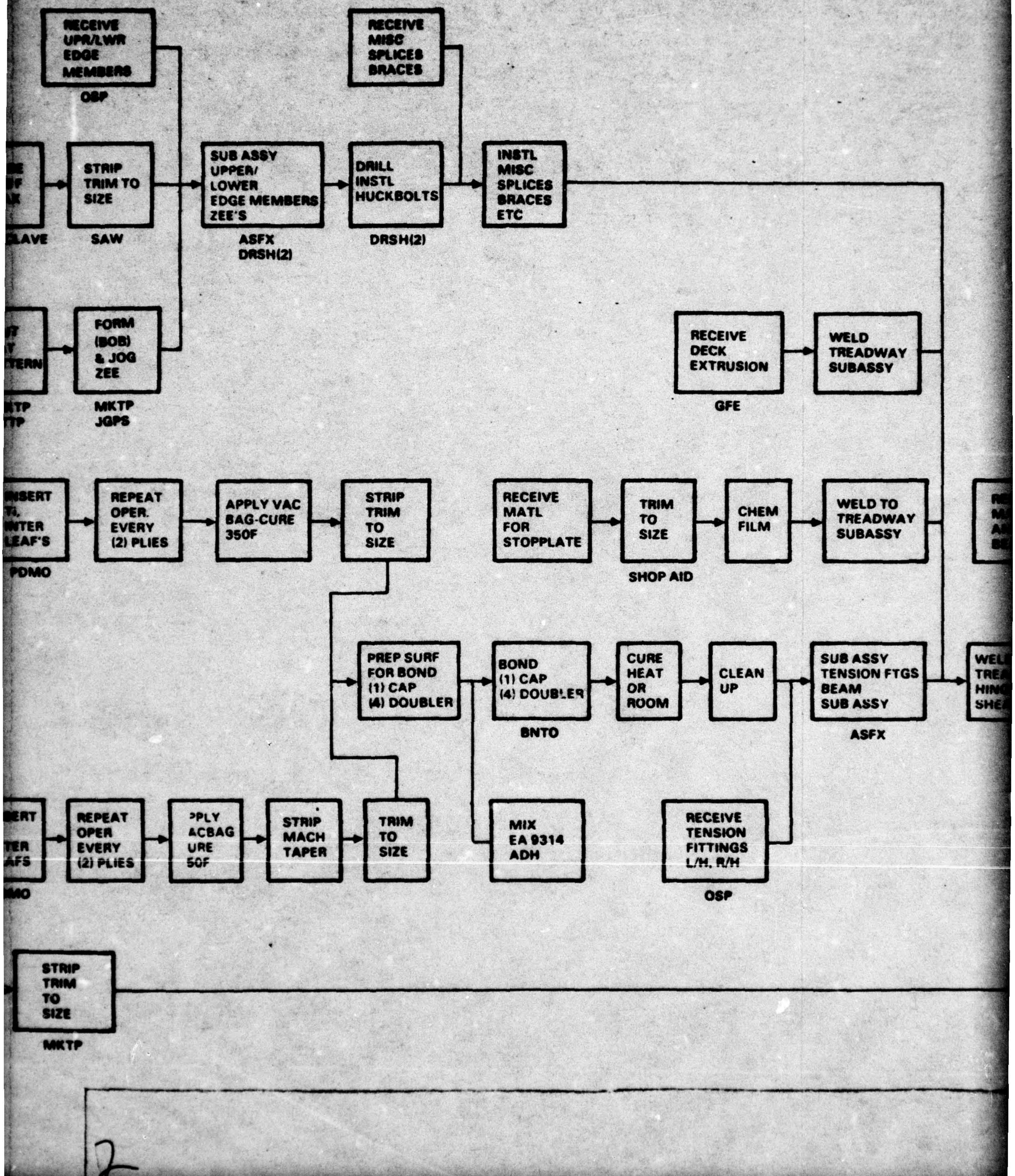


Figure 4.11. Composite Test Section Manufacturing Sequence and Flow


RECEIVE UPR/LWR EDGE MEMBERS
OSP
STRIP TRIM TO SIZE
SAW
SUB ASSY UPPER/ LOWER EDGE MEMBERS ZEE'S
ASFX DRSH(2)
RECEIVE MISC SPLICES BRACES
DRILL INSTL HUCKBOLTS
DRSH(2)
INSTL MISC SPLICES BRACES ETC
FORM (BOB) & JOG ZEE
MKTP JGPS
RECEIVE DECK EXTRUSION
GFE
WELD TREADWAY SUBASSY
REPEAT OPER. EVERY (2) PLIES
APPLY VAC BAG-CURE 350F
STRIP TRIM TO SIZE
PDMO
RECEIVE MATL FOR STOPPLATE
TRIM TO SIZE
SHOP AID
CHEM FILM
WELD TO TREADWAY SUBASSY
PREP SURF FOR BOND (1) CAP (4) DOUBLER
BOND (1) CAP (4) DOUBLER
BNTO
CURE HEAT OR ROOM
CLEAN UP
SUB ASSY TENSION FTGS BEAM SUB ASSY
ASFX
REPEAT OPER EVERY (2) PLIES
STRIP MACH TAPER
TRIM TO SIZE
MIX EA 9314 ADH
RECEIVE TENSION FITTINGS L/H, R/H
OSP
STRIP TRIM TO SIZE
MKTP

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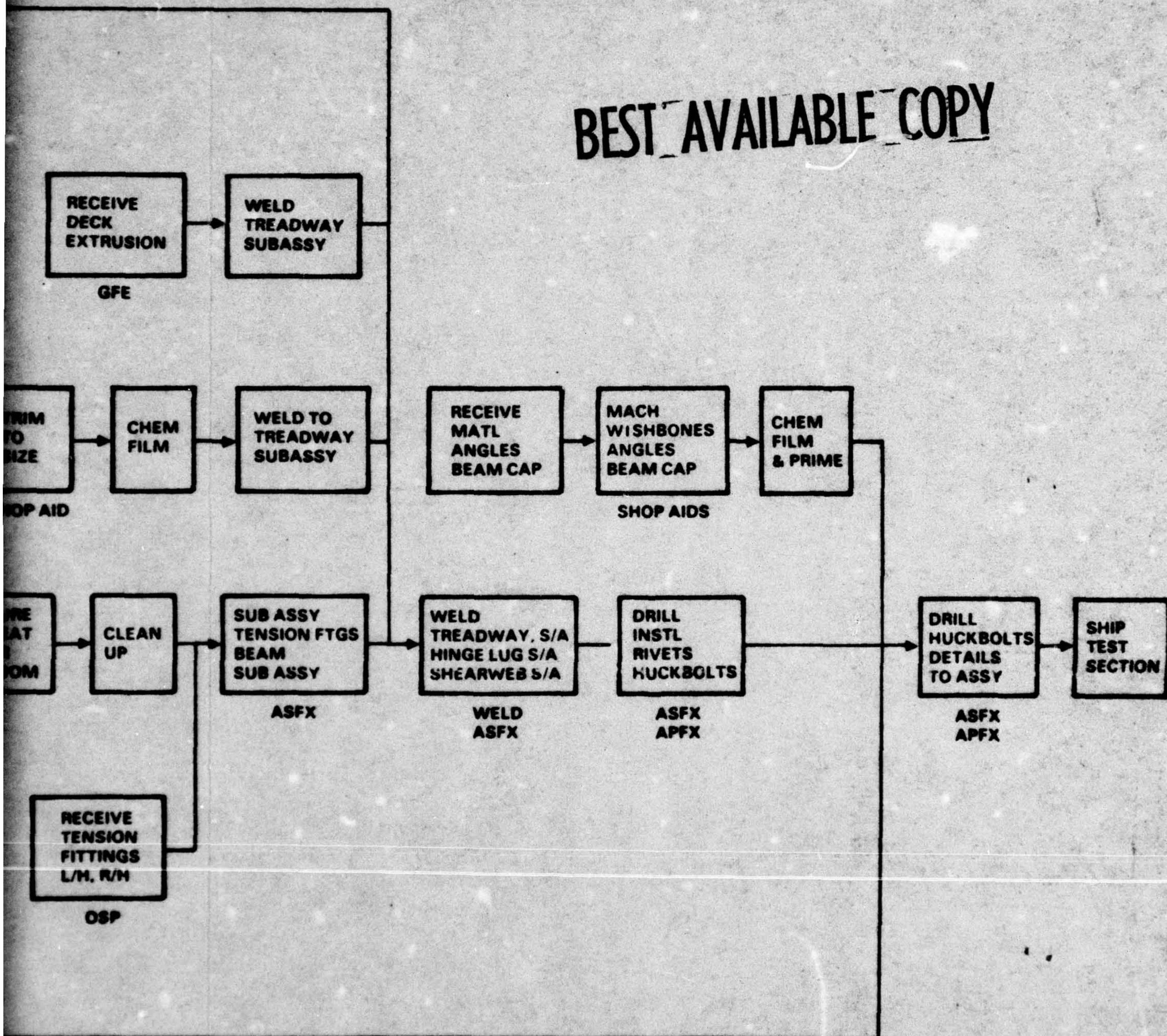


3. Assume no relocation or procurement of facilities are required.
4. The aluminum edge members will be purchased.
5. The stainless steel hinge lugs will be purchased.
6. The treadway extrusions will be GFE.
7. All laminates will be autoclave cured at 350°F and 100 psi.
8. All fastener holes will be hand drilled with a drill shell.

4.3.2 CTS TOOLING PLAN. The basic tooling plan was to provide minimum tools for the fabrication of all components. Wherever possible, "soft" tooling was to be provided to fabricate composite detail parts and shop aids would be used for machining metallic parts.

Tooling Ground Rules and Assumptions

1. The corrugated web will be laminated on a mold capable of producing two parts per layup.
2. All four tension caps will be laminated and cured at one time.
3. Tooling will be provided for accurately locating the titanium interleaves.

4.3.3 MANUFACTURING COST BREAKDOWN. The manufacturing cost breakdown (Table 4-5) presents estimated detail part fabrication costs, material costs, tooling costs, and assembly costs associated with the fabrication of two composite test sections.

Manufacturing Cost Ground Rules and Assumptions

1. All numbers are rough order of magnitude (ROM) estimates.
2. Tooling material dollars are based on $3.50 per tool manufacturing hour.
3. All manufacturing labor costs are based on $28/hr.

Table 4-5. CTS Manufacturing Cost Breakdown

PART NUMBER	QTY.	MATERIAL	MAT'L. COSTS (TOOL & PROD.)	FAB. COSTS	TOOL/SHOP AID COSTS (INC. PROD. ENG.)
72C0788-1	2	Assy.	$ 7,581	$ 11,480	$ 35,840
-3	2	S/A	723	1,344	8,008
-4	4	S/A	1,300	23,352	13,188
-5	2	Cres	760	750	N/R
-6	2	Cres	760	750	N/R
-7	2	Cres	1,530	740	N/R
-8	2	Cres	1,530	740	N/R
-9	8	Al	250	6,720	560
-10	4	Al	163	4,480	448
-11	8	Al	73	2,240	168
-12	4	Al	21	896	336
-13	6	Al extr.	GFE	3,024	4,764
-14	4	G/E	2,115	4,256	644
-15	4	G/E	7,695	9,128	19,460
-16	4	G/E	6,750	9,128	Use -15
-17	8	Al extr.	583	225	5,200 (vendor)
-18	4	Al	2	17	168
-19	8	Cres	69	1,008	168
-20	8	Cres	69	1,008	168
-21	8	Al	88	225	4,200 (vendor)
-22	32	Al	187	73	1,568
-23	4	G/E	12,700	11,788	6,916
-24	4	Al	25	1,120	168
-25	8	Al	58	280	168
Inserts	104	Ti	611	672	168
			$45,643	$95,444	$102,308

5

CONCLUSIONS

1. Application of advanced composite materials can substantially reduce the weight of the Army's Class 60 family of bridges.

2. While the use of composite materials projects a substantial unit cost for AVLBs, the savings in weight, added span, etc., can make this a cost effective method of bridge module construction. Particular attention must be payed to potential cost savings design refinements and material developments.

3. Composite development test articles demonstrated large safety margins while meeting target weights. This indicates a high degree of reliability.

RECOMMENDATIONS

It is recommended that the Army sponsor a subsequent program to design, fabricate, and field test a 7-meter composite bridge girder module.

It is recommended that a material and manufacturing technology study be sponsored by the Army to investigate the cost reduction potential of such items as:

1. Use of multiple ply broadgoods.
2. Automated panel layup.
3. Layup and cure of several parts concurrently.
4. Automated drilling, punching, and fastener installation.
5. Automated welding.
6. Use of precision forgings.
7. Automated final assembly.

APPENDIX A

DEVELOPMENT ARTICLE STRUCTURAL ANALYSIS

COMPOSITE TEST ARTICLE
LOWER TENSION CAP

Ultimate strength and fatigue analyses for the lower tension cap test component are presented in the following pages. For the materials considered, yield strength is not critical with the exception of bearing in the titanium interleaf reinforced joint and hence with this exception yield analyses are not given. The analyses are made for the maximum cap load obtained from the finite element analysis of the overall bridge. A fitting factor of 1.25 is applied in the analysis of the interleaf reinforced cap ends due to lack of test data for large joints of this configuration.

DESIGN LOADS

Maximum lower tension cap loads at mid span and at the end joints of the composite section from the overall finite element model of the bridge are as follows:

Location	Design Condition	Cond. No.	P
Mid Span	70 T. Wheeled Vehicle at Mid Span	10	198620#
Joint	70 T. Wheeled Vehicle at Mid Span	10	198395#

The lower cap test component is designed for a limit applied load of 200,000 lb.

MECHANICAL PROPERTIES

T300/5208 "A" Basis

$E_{11} = 20.5 \times 10^6$

$E_{22} = 1.47 \times 10^6$

$\mu = 0.3$

$G = 7.5 \times 10^5$

$\epsilon_{11}^{TU} = 8400\ \mu$ in/in

$\epsilon_{22}^{TU} = 7000\ \mu$ in/in

Titanium Sheet. Ti-6AL-4V Annealed. MIL-HDBK-5B

$F_{TU} = 134$ ksi

$F_{TY} = 126$ ksi

$F_{CY} = 132$ ksi

$F_{SU} = 79$ ksi

F_{BRU}

e/D = 1.5 = 197 ksi

e/D = 2.0 = 252 ksi

F_{BRY}

e/D = 1.5 = 171 ksi

e/D = 2.0 = 208 ksi

E = 16.0 msi

$\mu = 0.31$

AISI. 4340 Steel HT = 200 KSI MIL-HDBK-5B

F_{TU} = 200 ksi

F_{TY} = 176 ksi

F_{CY} = 181 ksi

F_{SU} = 120 ksi

F_{BRU}

e/D = 1.5 - 272 ksi

e/D = 2.0 - 355 ksi

F_{BRY}

e/D = 1.5 - 255 ksi

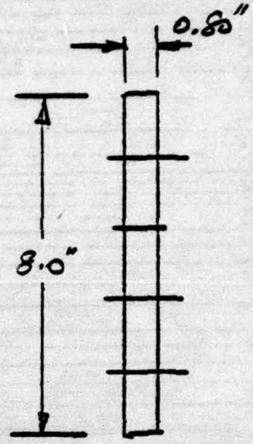
e/D = 2.0 - 280 ksi

E = 29.0 msi

μ = 0.32

BASIC CAP SECTION

The basic cap section is 8.0 in. by 0.8 in. as illustrated. The layup is $[0_2/\pm 45/0_2/\pm 45/0_2]_{4S}$ for a total of 80-10 mil plies of T300/934 graphite epoxy. The analysis is made for the maximum flange load of 200,000# from the F.E. analysis. A stress concentration factor of 2 is applied to the net section stresses at the 1/4 in. dia. web-flange attachment holes.



Design Load (Condition[10])
= 200,000# Limit

Stress on Net Section

$$= \frac{200{,}000}{0.8\ (8.0-4X.25} = \underline{35{,}714\ \text{psi}}$$

From laminate analysis the maximum strain in the axial (0°) plies is 2,627 μ in/in.

Allow strain $\epsilon_{11}^{TU} = 8{,}180\ \mu$ in/in

$$\text{M.S.} = \frac{\epsilon_{11}\ \text{Allow}}{1.5\quad \epsilon_{11}\quad K_T} = \frac{8180}{1.5 \times 2627 \times 2.0} - 1 = +0.038$$

FATIGUE

Based on available fatigue data for notched $[0/\pm 45]$ G/E, the expected fatigue life under fatigue cycling at a net section stress of 35,714 psi is greater than 10^7 cycles. Hence, the basic tension cap is not fatigue critical.

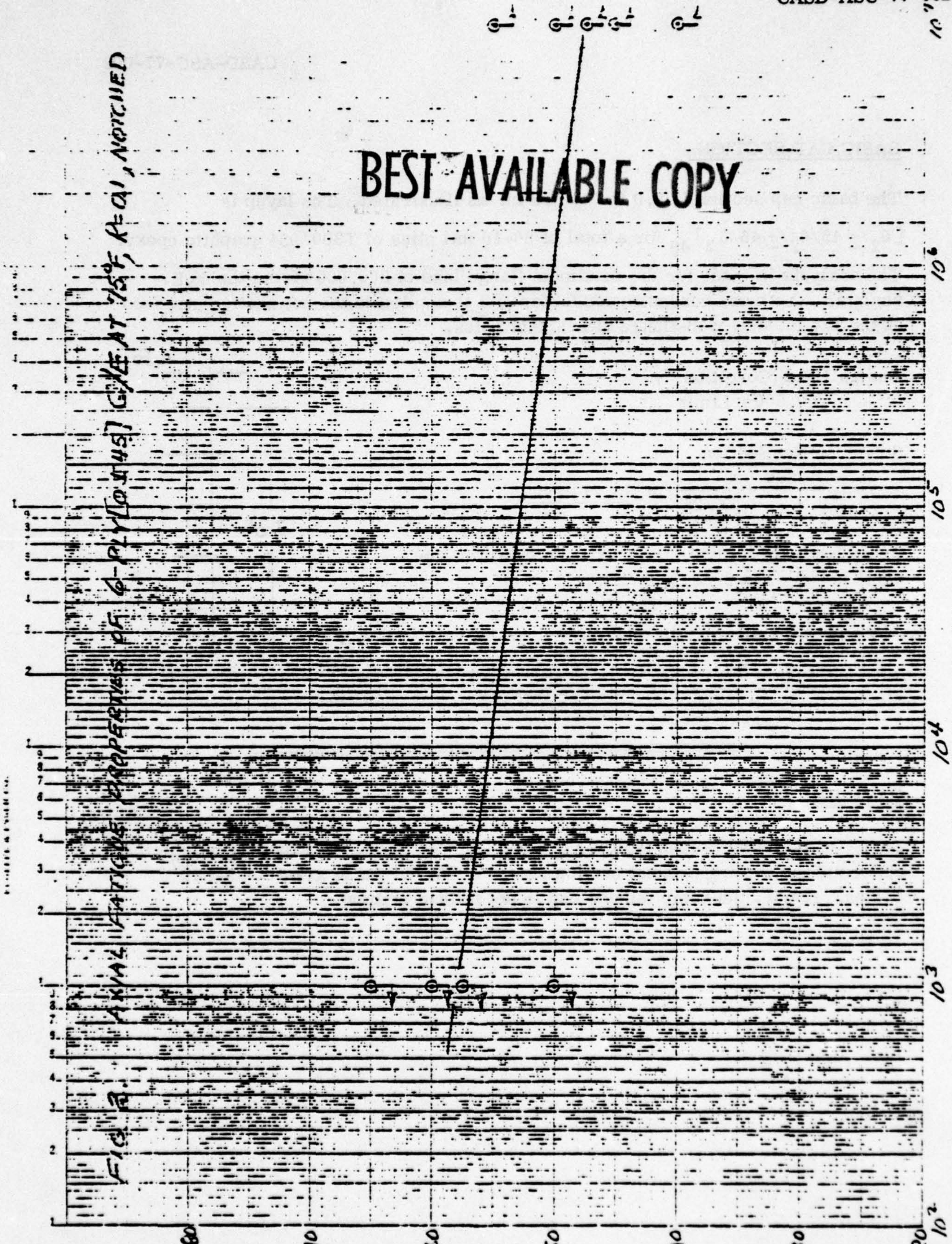
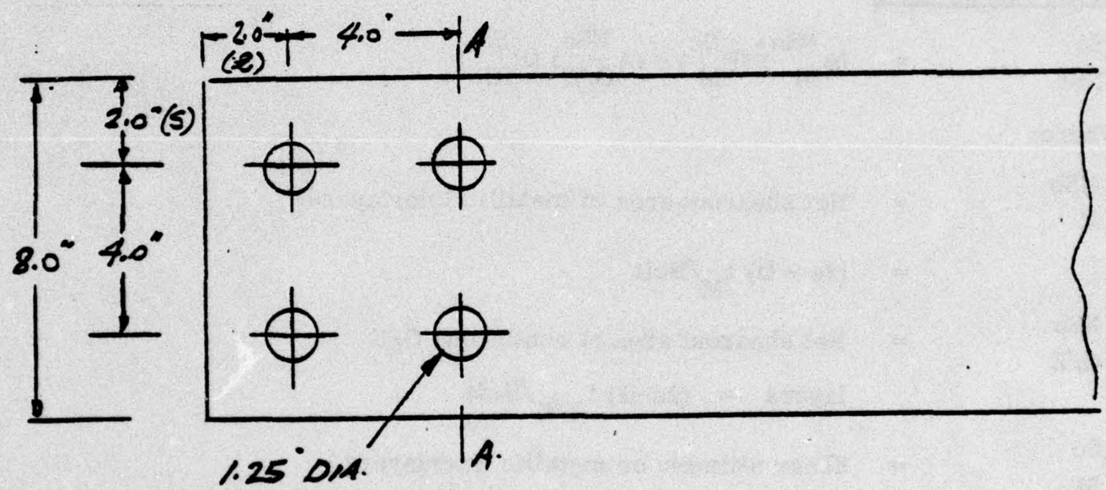


FIG. 2. AXIAL FATIGUE PROPERTIES OF 6-PLY [0/±45] G/E AT 75°F, R=0.1, NOTCHED

INTERLEAF JOINT ANALYSIS

The lower cap ends are reinforced by 26 - .020 in. thick titanium interleaves in the joint areas as shown in Figure 1. The interleaves replace the ± 45° plies in the basic cap and reinforcing doublers leaving the axial (0°) plies continuous. The interleaf joint analysis is based on the method presented in the AFML Advanced Composite Design Guide Ref. 1. A fitting factor of 1.25 is applied to the cap loads in the joint area.

Design Load = 200,000# (Limit).



Net Tension (Section A-A)

$$P^{Tu}_{Net} = 0.4\,[\,(A^{NS}_{M})\,(F^{Tu}_{M}) + (A^{NS}_{G/E})\,(F^{Tu}_{G/E})\,]$$

Where:

A^{NS}_{M} = Net area of metallic interlayers

$A^{NS}_{G/E}$ = Net area of continuous G/E laminate

F^{Tu}_{M} = Tension ultimate of metallic interlayers

= 134000 psi

$F^{Tu}_{G/E}$ = Tension ultimate of continuous G/E layers

= 172,200 psi

NET TENSION (Continued)

$$P^{Tu}_{Net} = 0.4 \left[26 \times .02\ (8.0 - 2.5)\ (134000) + .88\ (8.0-2.5)\ (172200) \right]$$

$$= \underline{486675\#}$$

$$\therefore \text{ M.S.} = \frac{P^{Tu}_{Net}}{(U.F)(K_F)P} - 1 = \frac{486675}{1.5 \times 1.25 \times 200{,}000} - 1$$

$$= \underline{+ 0.30}$$

BOLT SHEAR OUT

$$P^{So}_{Net} = (A^{NSo}_{M})\ (F^{So}_{M}) + (A^{NSo}_{G/E})\ (F^{So}_{Rib})$$

Where:

A^{NSo}_{M} = Net shearout area of metallic interlayers

= $(2e - D)\ t_M$/Bolt

$A^{NSo}_{G/E}$ = Net shearout area of continuous G/E layers = $(2e-D)\ t_{G/E}$/Bolt

F^{So}_{M} = Shear ultimate or metallic interlayers

$F^{So}_{G/E}$ = Shearout ultimate of G/E layers

Neglecting the shearout strength of the unidirectional G/E material.

$$P^{So}_{Net} = (2 \times 2 - 1.25)\ (26 \times .02)\ (79000)$$

$$= 112970\#/\text{Bolt}$$

Assuming 60% of the load is carried by the end bolt:

$$P = \frac{200{,}000}{4} \times 1.2 = 60{,}000\#$$

$$\therefore \text{ M.S (shear out)} = \frac{P^{So}_{Net}}{(U.F)(K_F)\ P.} - 1 = \frac{112970}{1.5 \times 1.25 \times 60{,}000} - 1 \ \underline{+0.00}$$

BEARING

$$P^{BRU} = A_M^{br} \cdot F_M^{bru} + A_{G/E}^{br} \cdot F_{G/E}^{bru}$$

Where:

A_M^{br} = Bearing area of metallic interlayers = Dt_M

$A_{G/E}^{br}$ = Bearing area or continuous G/E plies = $Dt_{G/E}$

F_M^{bru} = Bearing ultimate of metallic interlayers

= 197,000 psi

$F_{G/E}^{bru}$ = Bearing ultimate of G/E laminate.

Neglecting bearing on the unidirectional G/E layers.

P^{BRU} = 1.2 x 26 x .02 x 197000 = 128050#/Bolt.

Assuming 60% of the load is carried by the end bolts.

$$P = \frac{200{,}000 \times 1.2}{4} = 60{,}000\#$$

$$\therefore \text{M.S (Bearing)} = \frac{P^{Bru}}{(U.F.)(K_F)\,P} - 1 = \frac{128050}{1.5 \times 1.25 \times 60{,}000} - 1 = +0.14$$

BEARING YIELD ANALYSIS

F_M^{bry} = 171000 (Ti - 6 Al - 4v annealed e/D = 1.5)

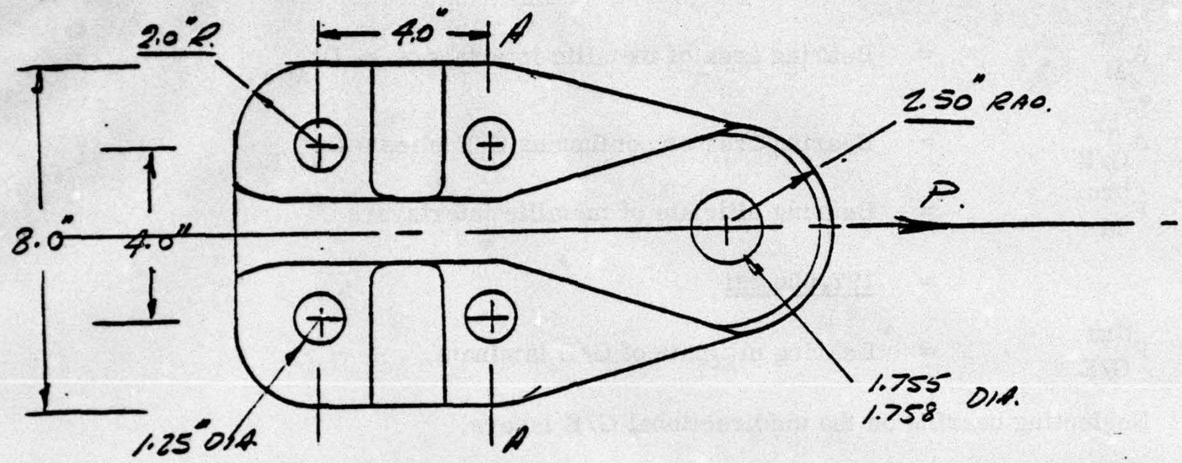
P^{bry} = 1.25 x 26 x .02 x 171000 = 111,150#

$$\text{M.S (Bearing yield)} = \frac{111150}{1.33 \times 1.25 \times 60{,}000} - 1 = +0.11$$

STEEL END FITTINGS

Material : 4340 steel H.T. = 200 - 210 K.S.I.

Design Load : 100,000 lb./fitting



END LUG ANALYSIS

The lug analysis is based on the method given in the G.D. Fort Worth Structures Manual.

1. TENSION ON NET SECTION

$P_{TU} = K \cdot \sigma_{TU} \cdot A_T$ $\lambda = \frac{D}{W} = \frac{1.75}{2 \times 2.5} = 0.35$

$= .88 \times 200{,}000 \times 3.18$ $\therefore K_T = 0.88$

$= \underline{558835}$ lb $A_T = .98\,(5.0 - 1.76)$

$= 3.18 \text{ in}^2$

$\therefore$ M.S. $= \frac{558835}{1.5 \times 100{,}000} - 1$

$= \underline{\underline{+2.73}}$

2. LUG YIELD LOAD

$e/D = \frac{2.5}{1.75} = 1.43$ $K_{BY} = 1.4$

$P_Y = K_{BY}\, A_{BR}\, \sigma_{TY} = 1.4\,(1.75 \times .98)\, 175000 = 420175$ lb.

$\therefore$ M.S. $= \frac{P_y}{1.33 \cdot P.} - 1 = +2.16$

LUG ANALYSIS (Continued)

3. Shear tearout, bearing, hoop tension anslysis

$$e/D = \frac{2.5}{1.75} = 1.43 \qquad D/t = \frac{1.75}{.98} = 1.79$$

$$\therefore \quad K_{BR} = 1.4$$

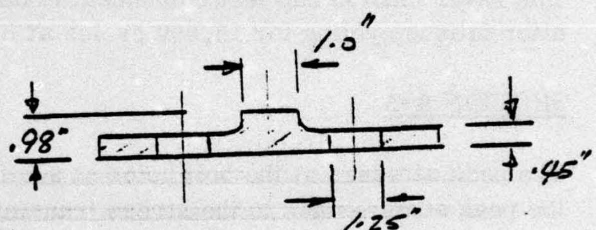
$$P_{BRU} = K_{BR} \cdot \sigma_{TU} \cdot A_{BR}$$

$$= 1.4 \times 200{,}000\ (1.76 \times .98) = 492800 \text{ lb.}$$

$$\therefore \text{M.S.} = \frac{P_{BRU}}{1.5\ P} = 1 = \frac{492800}{1.5 \times 100{,}000} - 1 = +2.29$$

SECTION A - A

Axial tension load = 100,000#



$$\text{Area} = .45\ (8.0 - 2.50) + 1.0\ (.98 - .45)$$

$$= 3.01^{\ 2}$$

$\therefore$ Tension stress on Section

$$f_t = \frac{100{,}000}{3.01} = 33278 \text{ psi}$$

$$F_{TU} \text{ (4340 steel)} = 200{,}000 \text{ psi}$$

$$\therefore \text{M.S.} = \frac{F_{TU}}{1.5.f.} - 1 = \frac{200{,}000}{1.5 \times 33778} - 1 = +3.01$$

BEARING AT ATTACHMENT HOLES

$$\text{Bearing stress } f_{br} = \frac{S}{Dt}$$

Assuming a peaking factor of 1.2

$$\text{Max. Bolt shear} = \frac{100{,}000}{4} \times 1.2 = \underline{30{,}000\#}$$

$$\therefore f_{br} = \frac{30{,}000}{1.25 \times .45} = \underline{53333 \text{ psi}}$$

$$e/D = \frac{2.0}{1.25} = 1.6$$

$$F_{BRY} = 272 \text{ ksi}$$

$$F_{BRU} = 255 \text{ ksi}$$

$$\therefore \quad M.S. = \frac{F_{BRU}}{1.5\,(f_{br})} - 1 = \frac{272000}{1.5 \times 53333} - 1 = +2.4$$

FATIGUE ANALYSIS

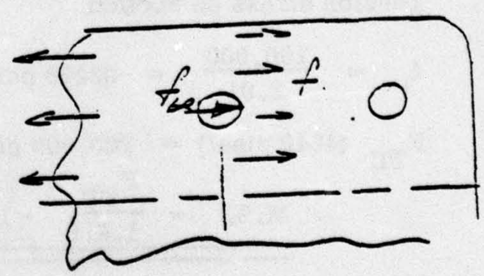
The lower tension cap test component is designed to develop the ultimate test load after fatigue cycling for 15,000 cycles at limit load.

SECTION A-A

The peak stresses at the bolt holes at section A-A are evaluated by superimposing the peak stresses due to the stress transmitted across the holes and the bearing stress at the attachment holes. Elastic stress concentration factors obtained from "Stress Concentration Design Factors" by Peterson are used.

Assuming 50% of time loss on Section A-A is transmitted to the 2nd pair of bolts.

$$\therefore \quad f = \frac{33278}{2} = 16639$$



From Peterson Fig. 69 with $\frac{D}{W} = .31$

$$K_T = 2.35$$

Again assuming equal loads on all bolts:

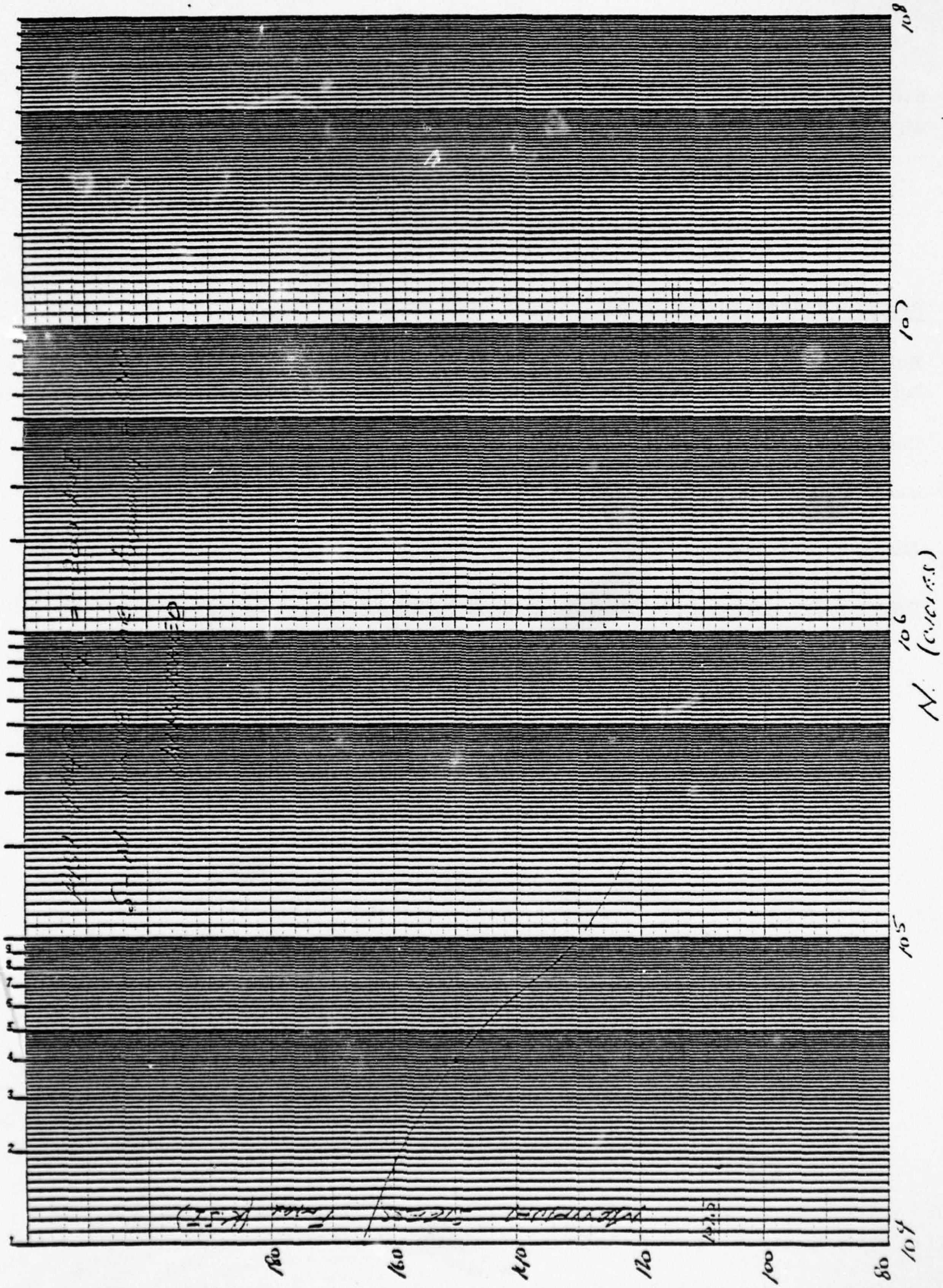
$$f_{br} = \frac{P}{N.D.t.} = \frac{100,000}{4 \times 1.25 \times .45} = 44444 \text{ psi}$$

From Peterson Fig. 83 with $\frac{D}{W} = .31$

$$K_{BR} = 1.54$$

$$\therefore \quad f_{MAX} = f.K_T = f_{br}\,K_{BR}$$

$$= 16639 \times 2.35 = 44444 \times 1.54 = 107546 \text{ psi}$$


N (CYCLES)
10^4
10^5
10^6
10^7
10^8
180
160
140
120
100
80

From S-N curve for unnotched 200 HT - 4340 steel with f_{MAX} = 107546 psi. The expected fatigue life N cycles $> 10^7$.

$\therefore$ Fatigue damage $= \dfrac{n}{N} = \dfrac{15000}{\infty} = 0.0$

$\therefore$ Section is satisfactory for fatigue.

BOLTS - END FITTING TO CAP

End fittings are attached to reinforced ends of cap by 4 - 1 1/4 inc. dia., 125 K.S.I. bolts in double shear.

Design load on joint = 200,000# (Limit)

Assuming a peaking factor of 1.2

Maximum bolt load $= \dfrac{200{,}000}{4} \times 1.2 = \underline{\underline{60000\#}}$

Double shear strength of 1 1/4 in. dia., 125 KSI bolt

$$= 92000 \times 2 = \underline{\underline{184000}}\text{ lb.}$$

$$\therefore \text{M.S.} = \frac{S^{ULT}}{(\text{U.F})\,(K_P)\,S} - 1 = \frac{184000}{1.5 \times 1.25 \times 60000} - 1 = +0.63$$

CORRUGATED PANEL - TEST COMPONENT

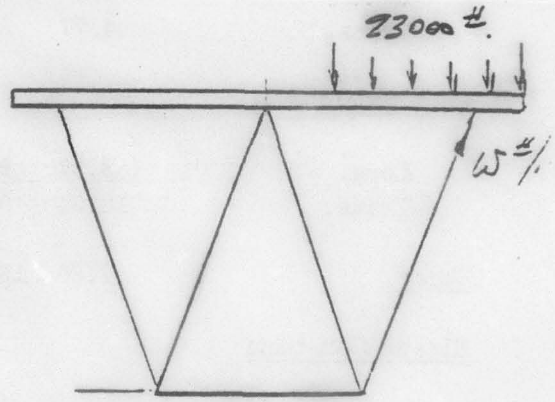
STRUCTURAL ANALYSIS

The test panel shown in Figure 2 represents a typical portion of the proposed corrugated shear webs away from the reinforced end bays. The edge members and joints are representative of the proposed method of attachment to the bridge deck. The specimen is analyzed for strength and stability under the maximum local transverse edge loading arising from the critical maximum single wheel loading condition.

DESIGN LOADS

The maximum edgewise compression load intensity on the deck support webs is given by the maximum single wheel load condition (20000 x 1.15 = 23000 lb) with the outer edge of the wheel located at the extreme edge of the bridge deck as shown.

For this condition the maximum load intensity (ω) in the critical webs = 525 #/in. (limit).



MATERIAL PROPERTIES

The web laminate is comprised of .08 in. $[0_2/\pm45_3]_s$ T300/734 graphite epoxy with outer plies of .01 in. thick 181 Kevlar fabric at 45^o. The mechanical properties used for the G/E are 'A' basis properties developed for T300/5208. The 181 Kevlar properties are from the Dupon Kevlar Data Manual.

LAMINA PROPERTIES

Property	T330/5208 Design Ultimate Stress (KSI)	μ in/in	181 Kevlar Design Ultimate Stress (KSI)	μ in/in
Tension				
Long.	171.9	8400	73.0	
Trans.	4.77	7000		
Compression				
Long.	188.57	9200	21.0	
Trans.	13.54	9200		
Shear	7.86	15000	16.0	
Elastic Constants				
E. Long.	20.5 msi		4.0 msi	
E. Trans	1.47 msi		4.0 msi	
μ	.3		.12	
G	0.52 msi		0.30 msi	

MATERIAL PROPERTIES (Continued)

The mechanical properties for $[0_2/\pm45]_s$ G/E laminate with .01 181 Kevlar outer plies derived from the foregoing lamina properties using GD/Convair's laminate analysis program are as follows:

Elastic Constants

$E_x = 5.96 \times 10^6$ psi

$E_y = 3.29 \times 10^6$ psi

$\mu = 0.74$

$G = 3.69 \times 10^6$ psi

Bending Stiffness Matrix

$$D = \begin{matrix} 447.92 & 272.3 & -40.701 \\ & 358.53 & -40.701 \\ & & 277.76 \end{matrix}$$

Ultimate Allowables

$$F^{X}_{TU} = 50120 \text{ psi}$$

$$F^{Y}_{TU} = 23000 \text{ psi}$$

$$F^{X}_{W} = 54890 \text{ psi}$$

$$F^{Y}_{CU} = 30260 \text{ psi}$$

$$F^{SY}_{SU} = 51660 \text{ psi}$$

Laminte Strength Analysis

Basic Laminate

Transverse compression loading $N_X = -525$ #/in.

$$\sigma_C = \frac{N_X}{t} = \frac{-525}{.1} = -5250 \text{ psi}$$

F_{OU} = 54890 psi (Ref. Pg. 3)

$$\therefore \quad M.S. = \frac{54890}{1.5 \times 5250} - 1 = +5.97$$

Net Section at Bolted Joints

Bolted joint tests of G/E laminates with small diameter bolt holes exhibit ultimate stress concentration factors of approximately 1.5. Conservatively assuming $K_T = 2.0$ and a net section factor $K_n = 0.75$ at the joints. The margin of safety at the net section is given by:

$$M.S. = \frac{K_n F_{Tu}}{K_T \sigma_C} - 1$$

$$= \frac{.75 \times 54890}{2.0 \times 5250} - 1 = +2.92$$

PLATE BUCKLING ANALYSIS

The 4.0 in. wide panels at the crown or the corrugations are critical. The panels are treated as long simply supported orthotropic plates.

The critical axial compression loading is given by:

$$N_{x_{en}} = \frac{2\pi^2}{b}\left\{\sqrt{D_{11}D_{22}} + D_{12} + 2\ D_{66}\right\}$$

$$= \frac{2\pi^2}{4}\left\{\sqrt{447.92 \times 358.53} + 277.3 + 2 \times 277.76\right\}$$

$$= 1516\ \#/\text{in.}\quad \left(F_{en} = \frac{Mx_{en}}{t} = 15160\ \text{psi}\right)$$

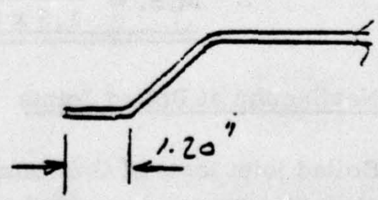
The applied load intensity $= M_x = 525\ \#/\text{in.}$

$$\therefore \text{M.S} = \frac{N_{xen}}{1.5N_x} - 1 = \frac{1516}{1.5 \times 525} - 1 = +0.93$$

PANEL EDGES

The panel edges are treated as long simply supported plates with one long edge free.

The critical axial compression loading is given by:



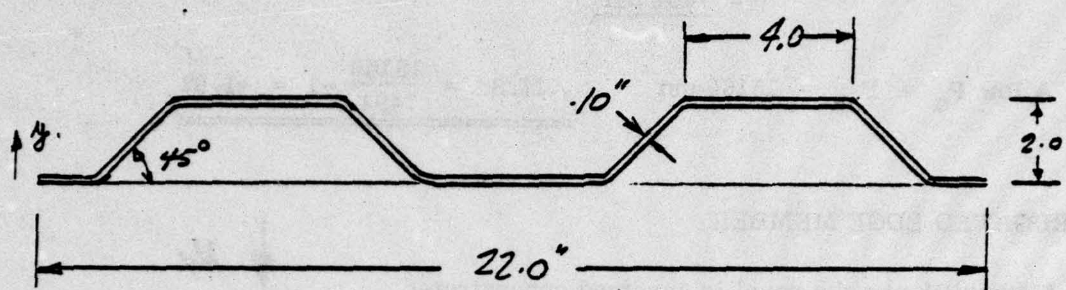
$$N_{x_{en}} = \frac{h^g}{b^2} = G_{xy} = \frac{12D_{66}}{b^2} = \frac{12 \times 277.76}{1.22}$$

$$= \underline{2315\ \#/\text{in.}}$$

$$\text{M.S.} = \frac{N_{x_{en}}}{1.5N_x} - 1 = \frac{2315}{1.5 \times 525} - 1 = +1.94$$

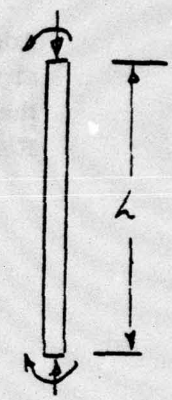
COLUMN BUCKLING ANALYSIS

SECTION PROPERTIES



FOR THE SECTION SHOWN

$A = 2.515 \text{ In.}^2$
$\overline{Y} = 1.060$
$I = 1.615 \text{ In.}^4$



DESIGN LOAD

$$P = N_x L = 525 \times 22$$
$$= 11550 \text{ lb Limit}$$
$$= \underline{17325 \text{ lb Ultimate}}$$

Since the centroid of the Section ($\overline{Y}$) is not at mid height end moments are applied. Hence, panel is analyzed as a beam column with end moments.

$$M_1 = P(\overline{Y} - R/2) = 17325\,(1.06 - 1.0)$$
$$= \underline{1040 \text{ in lb. Ultimate}}$$

The maximum B.M. is given by:

$$M = M_1 \text{ Sec } \left(\frac{L}{2J}\right) \qquad J = \sqrt{\frac{EI}{P}}$$

$$= 1040 \text{ Sec } \left(\frac{35}{2 \times 555.58}\right) \qquad = \sqrt{\frac{5.96 \times 10^6 \times 1.615}{17325}}$$

$$= \underline{1040.5 \text{ In. lb.}} \qquad = 555.58$$

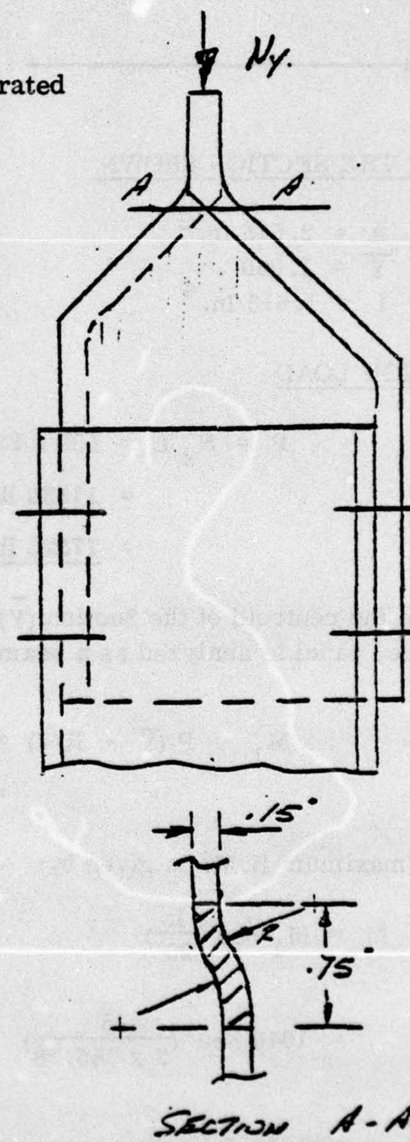
$$\therefore \text{Max. Stress} = \frac{-17325}{2.515} - \frac{1040.5\ (2.0-1.06)}{1.615}$$

$$= \underline{7494 \text{ psi}}$$

Allow $F_c = F_{cr} = 15160$ psi $\quad \therefore M.S. = \frac{15160}{7494} - 1 = +1.02$

CORRUGATED EDGE MEMBER

Edge loading (N_y) on the panel is assumed concentrated at the direct load path provided by the 45° web of the corrugation. These webs are at 6.0" spacing. Ref. Figure 2.



Load/Web

$= 6\ N_y$

$= 6 \times 788$

$= 4728$ lb. Ultimate

An effective length of -.75 In. at Section A-A is assumed.

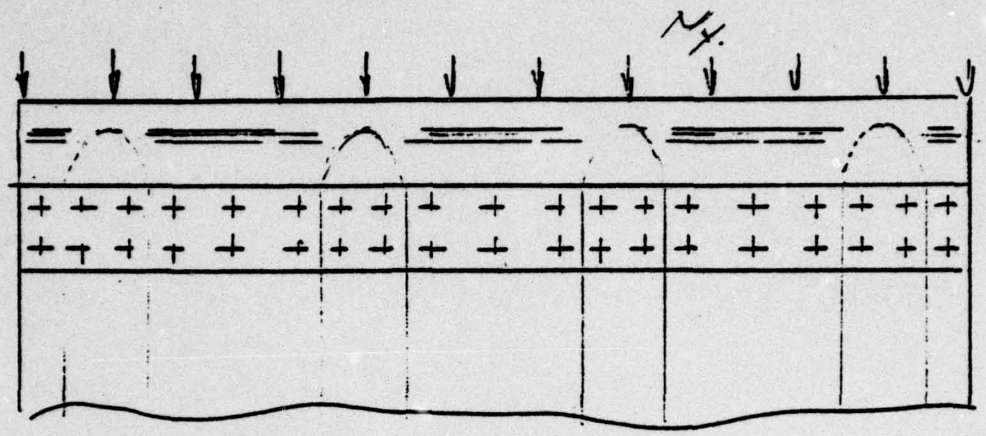
$$\therefore f_c = \frac{4728}{.75 \times .15}$$

$= 42027$ psi

F_{cy} (7005 - T53) $= 45000$ psi

$$\therefore M.S. = \frac{45000}{42027} - 1 = +0.07$$

EDGE MEMBER ATTACHMENTS



The 0.16 In. 7005 AL edge member is attached by 3/16 In. dia. titanium cherry buck rivets as shown.

Assuming a 1.2 peaking factor, the maximum load/attachment(s) is:

$$S = \frac{1.2.\ \overline{\sigma}_{Max.}\ b.t.}{n} = \frac{1.2 \times 7494 \times 4.0 \times 1.0}{6}$$

$$= \underline{\underline{599.5\#}}$$

FASTENING SHEAR

Single shear strength 3/16" dia. Ti. Cherry Buck

$$= \underline{\underline{2600\#}}$$

Bearing in 7005 Al. Web

$$P_{BCU} = F_{BCU}\ D.t. =$$

BEARING IN G/E WEB

For bearing in the composite web, the strength of the outer Kevlar plies is neglected F_{BCU} for $(O_2/\pm 45)$ G/E = 110,000psi.

$$\therefore P_{BRU} = F_{BRU}\ D.t = 110{,}000 \times .1875 \times .08$$

$$= 1650\#$$

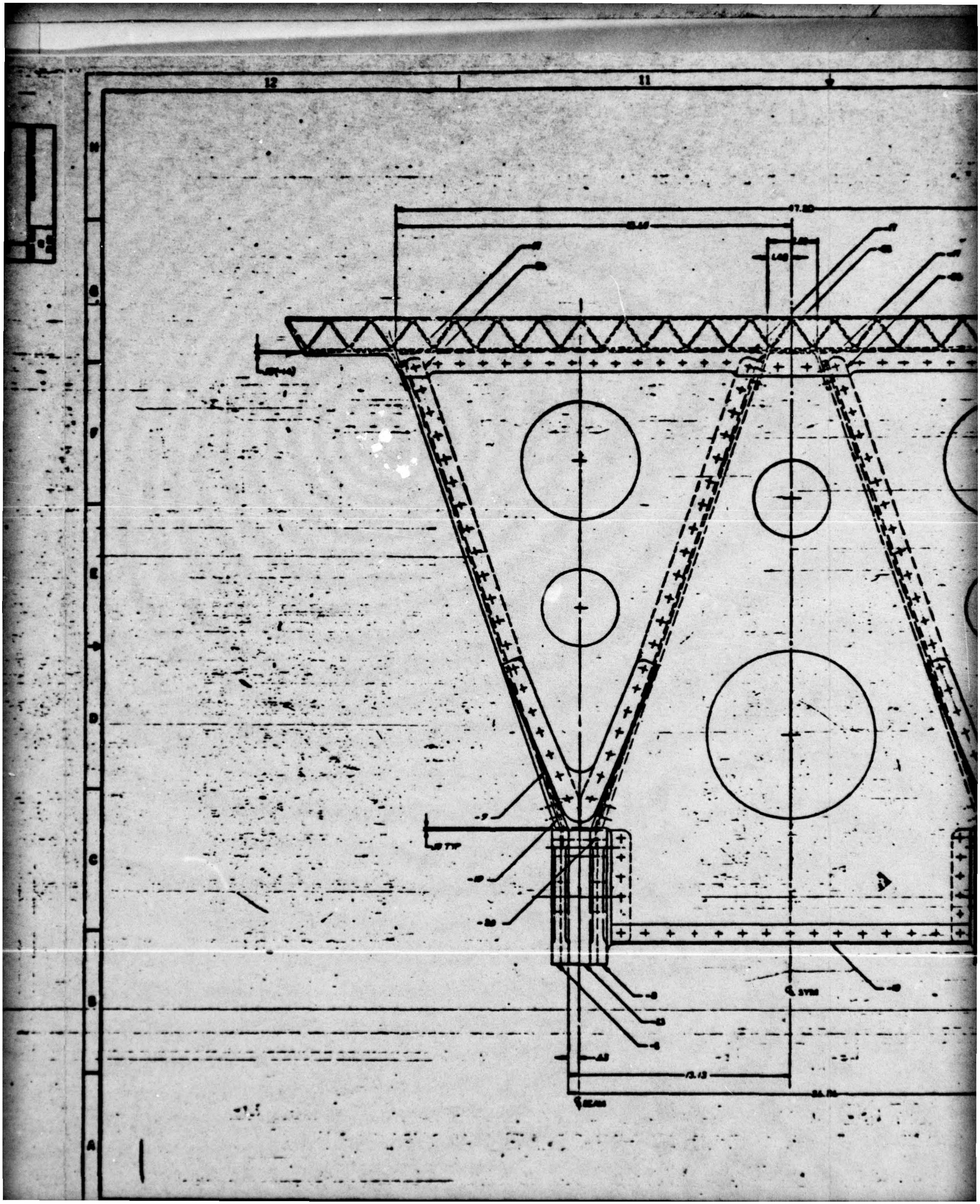
$$\therefore M.S. = \frac{1650}{599.5} - 1 = +1.75$$

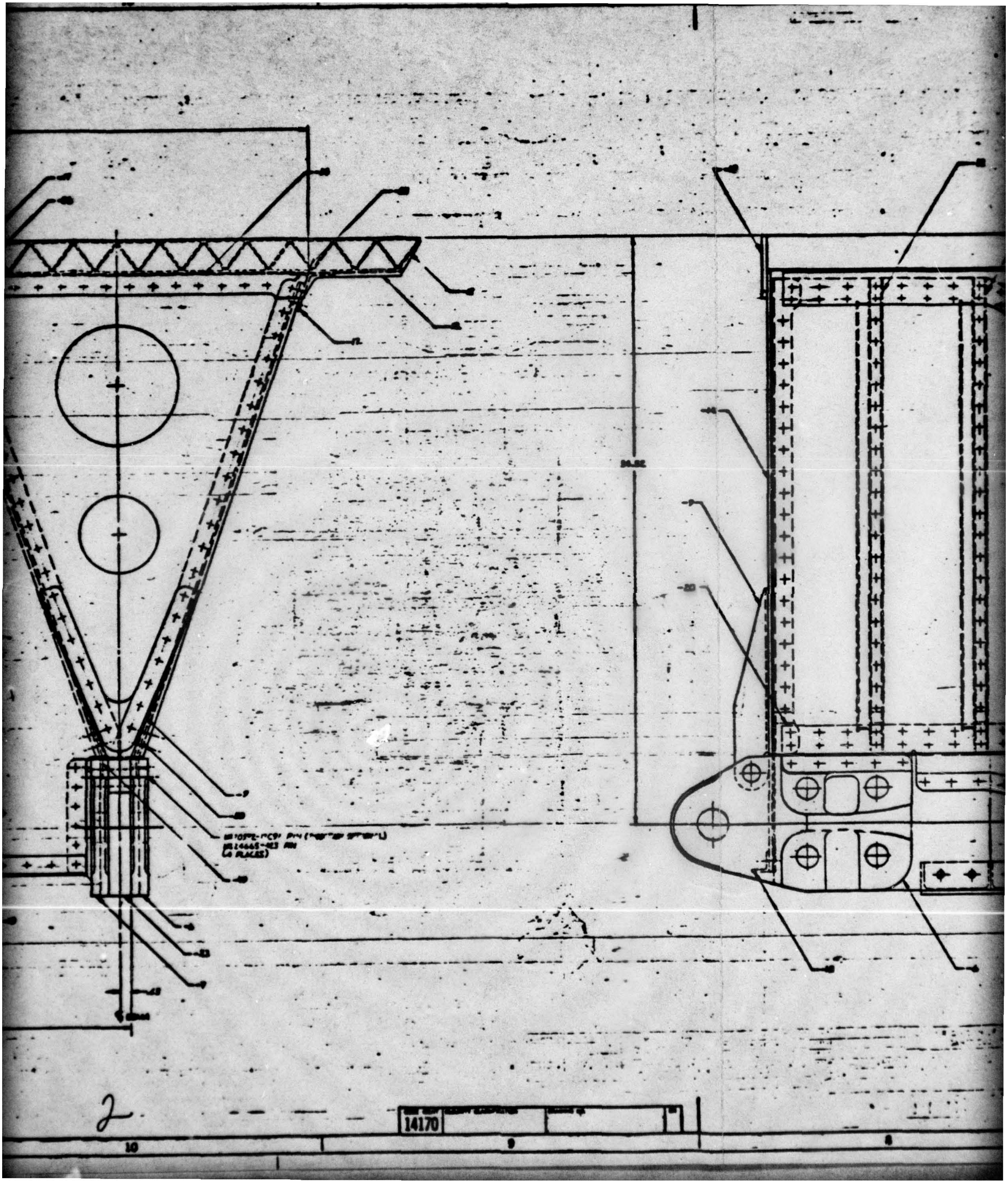
APPENDIX B

Drawing Number 72C0788

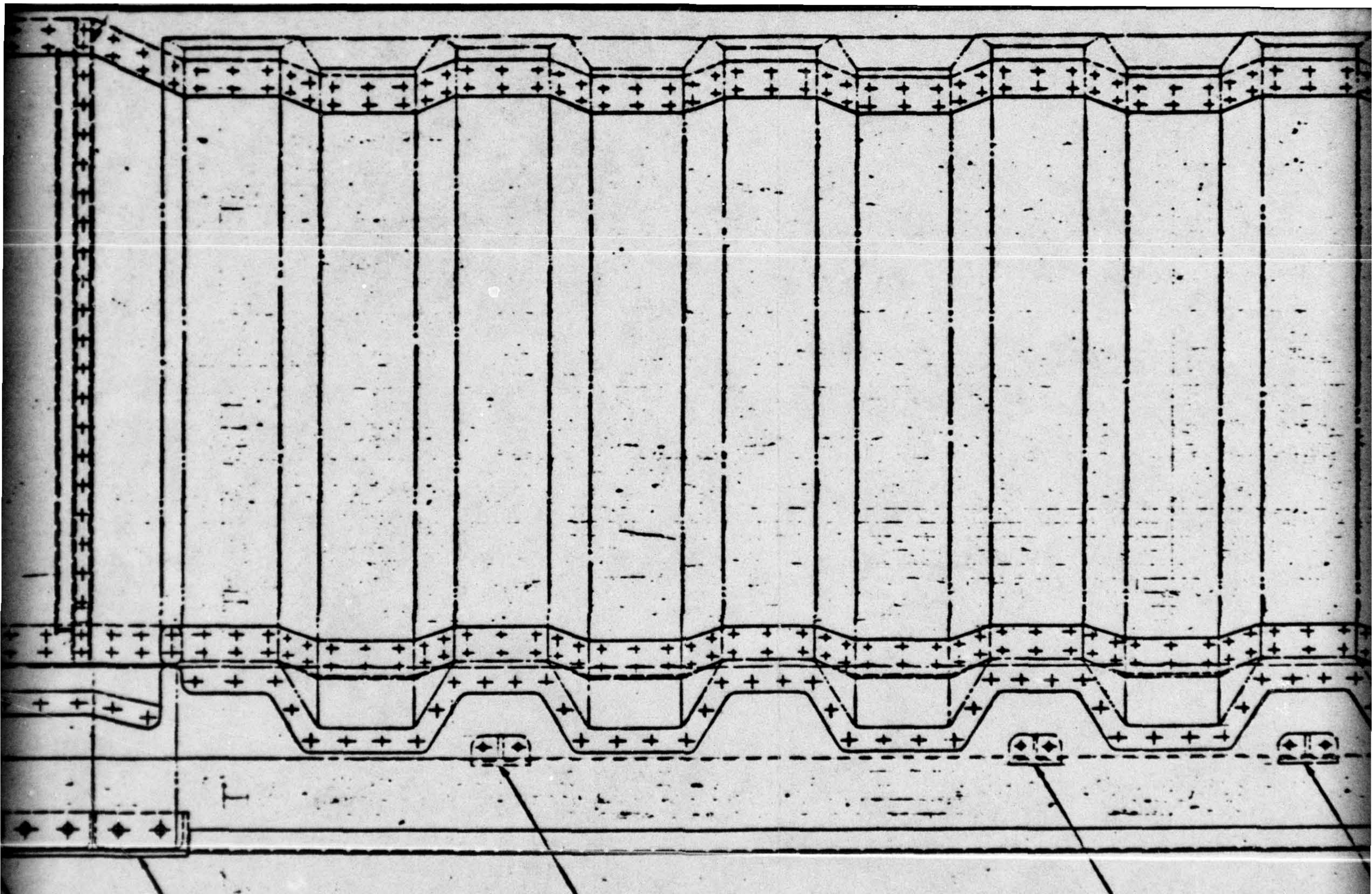
Composite Test Section (CTS) -

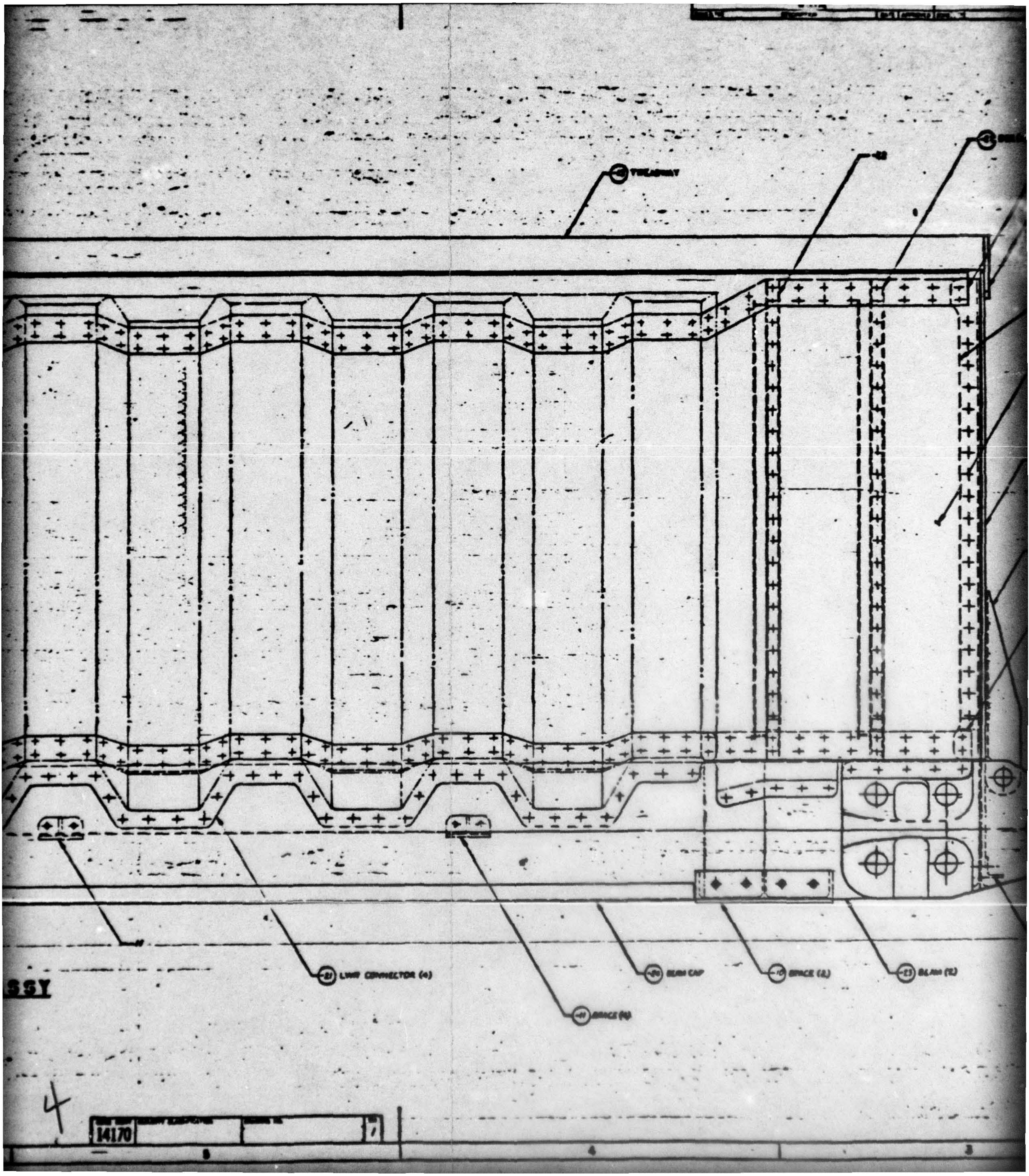
Armored Vehicle Launched Bridge


12
11



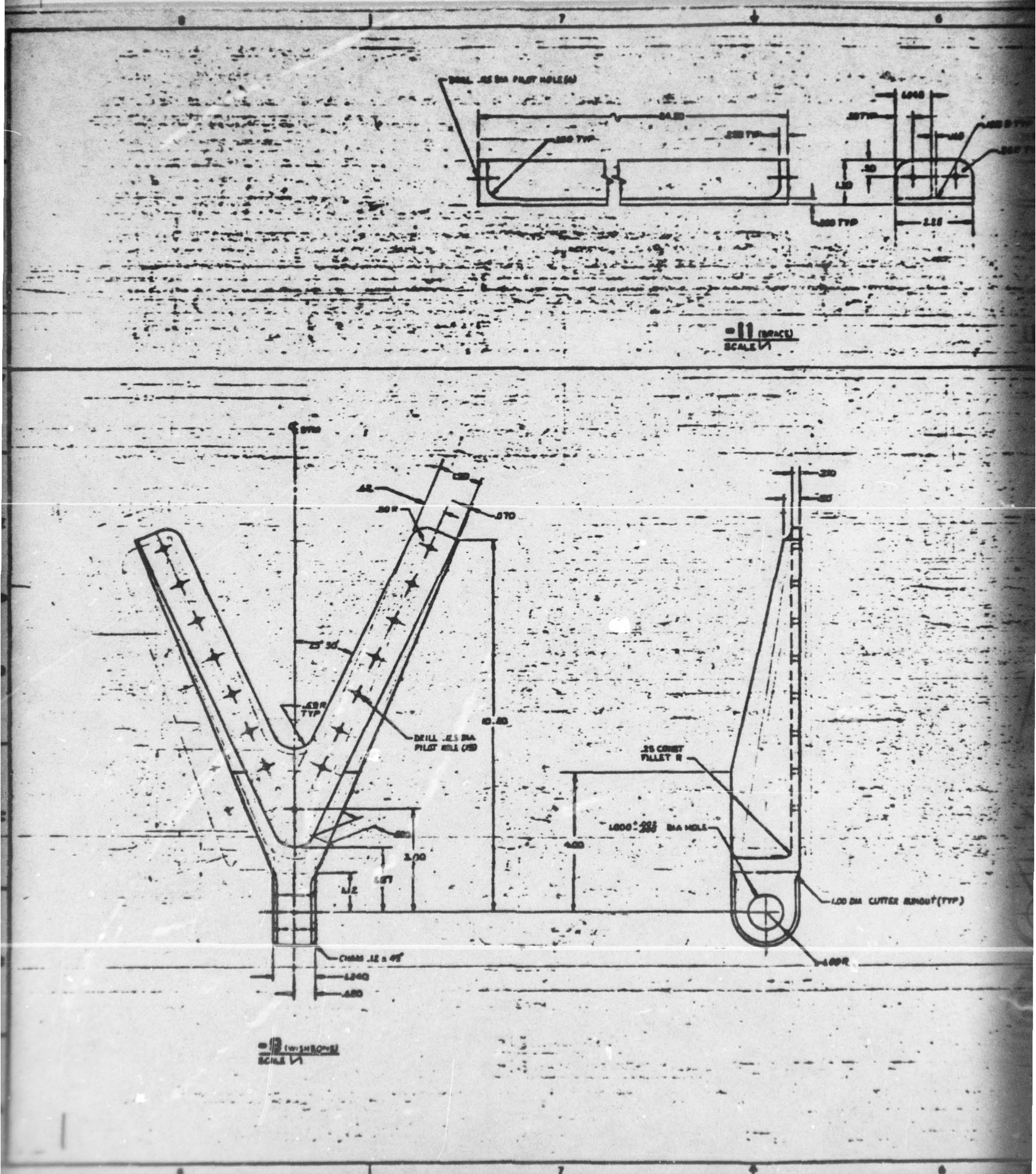
(4 PLACES)
14170
10
9
8
2


-1 ASSY

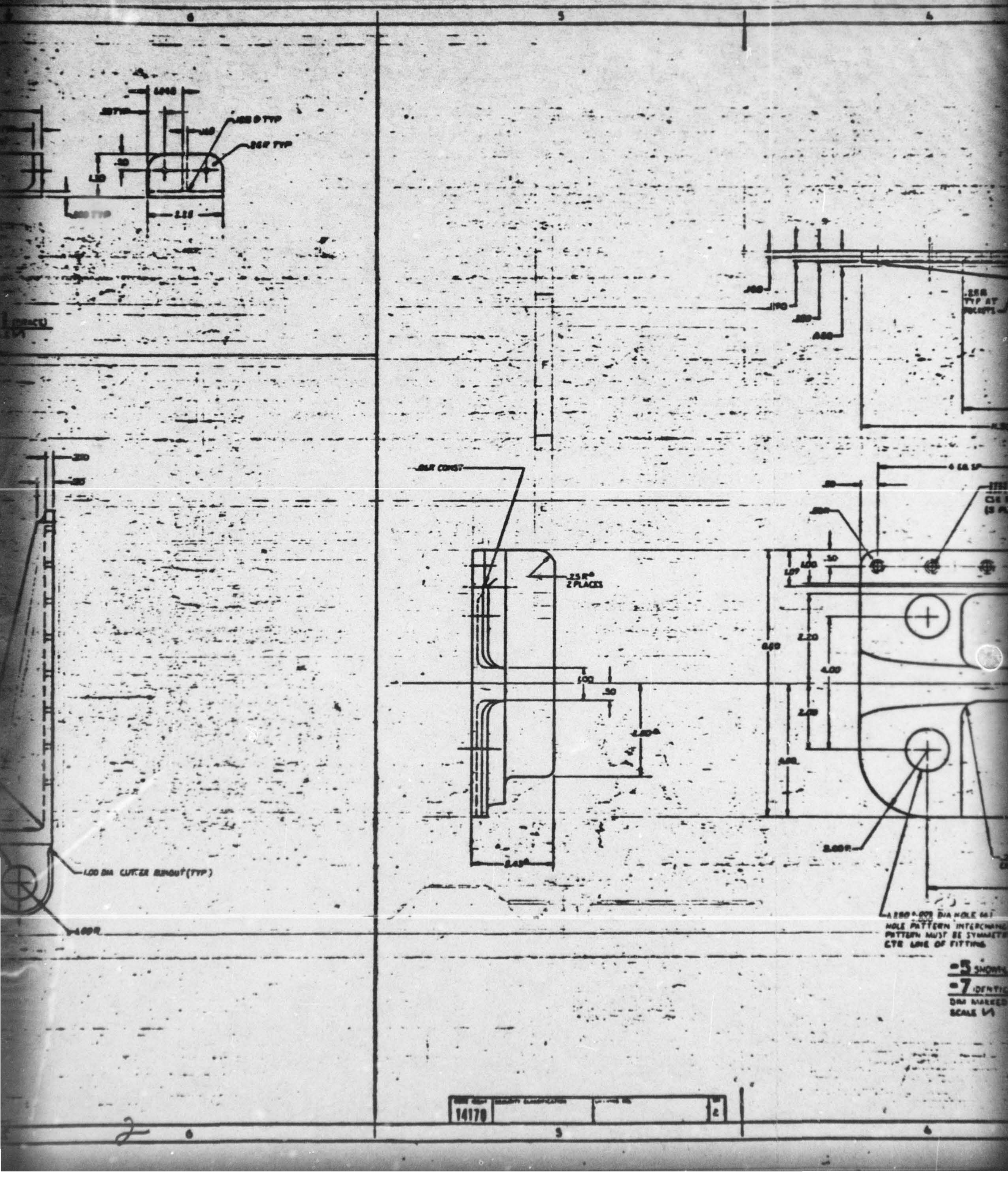


TREADWAY
LINK CONNECTOR (4)
BEAM CAP
BRACE (2)
BEAM (2)
BRACE (6)
SSY
14170

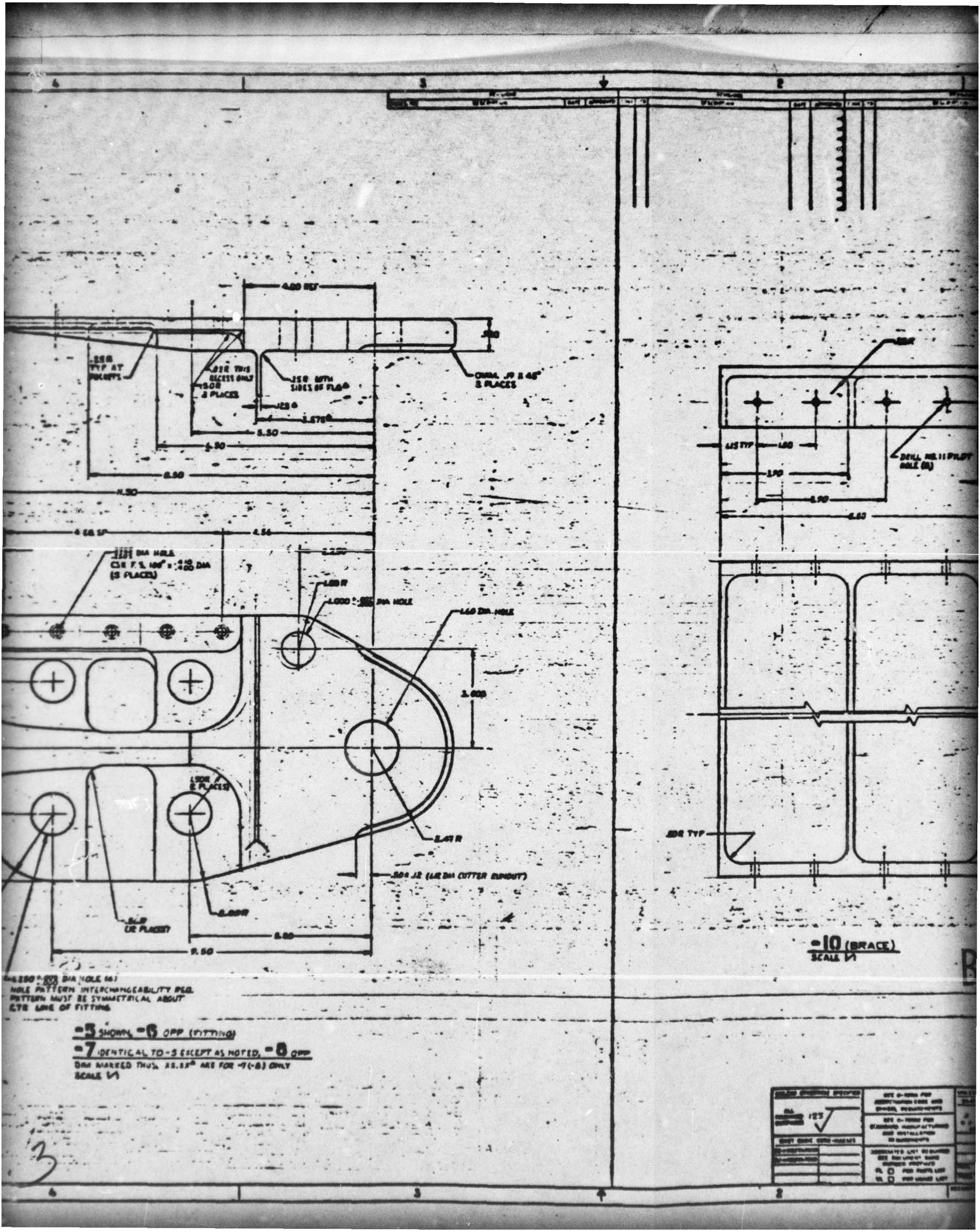
4

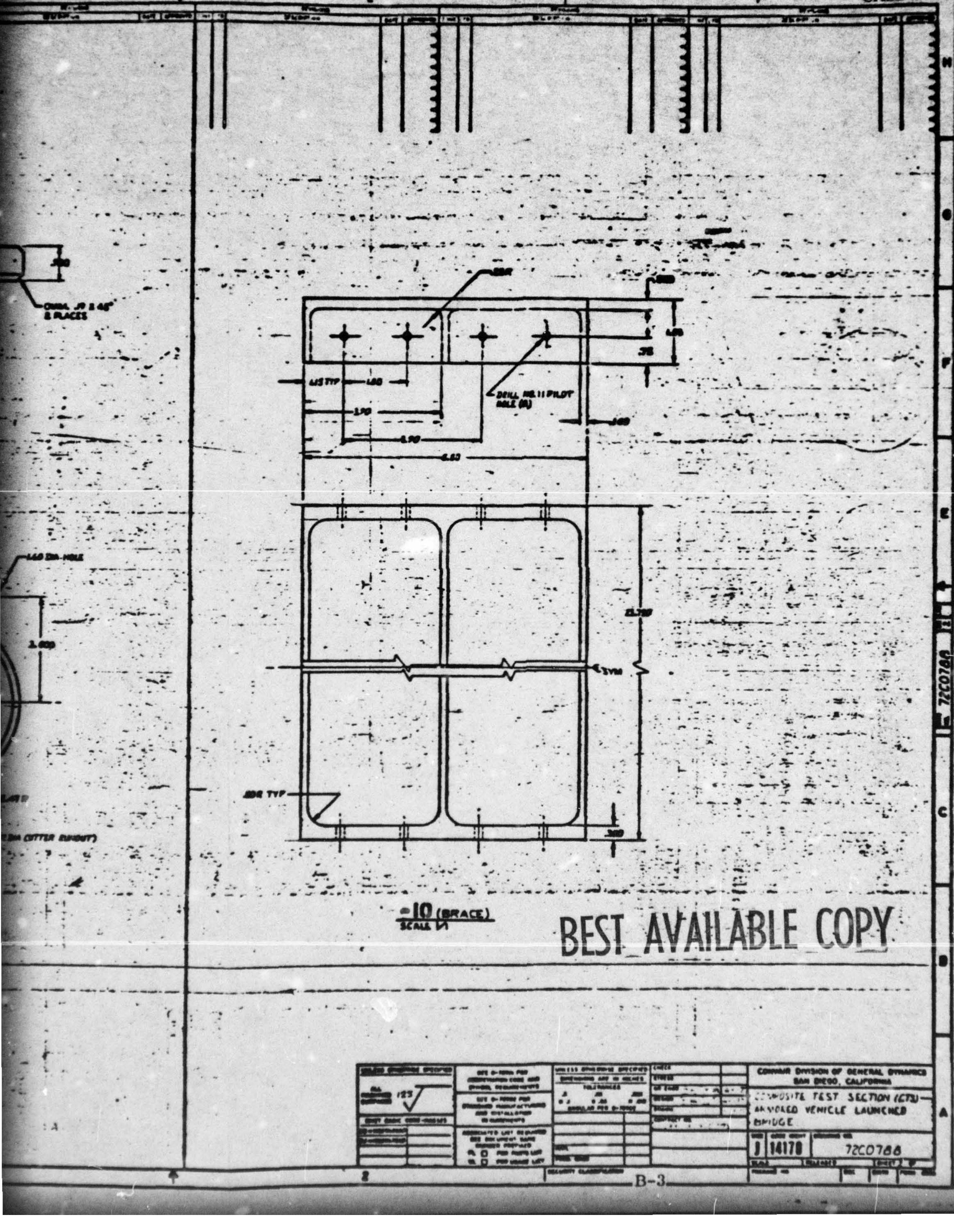


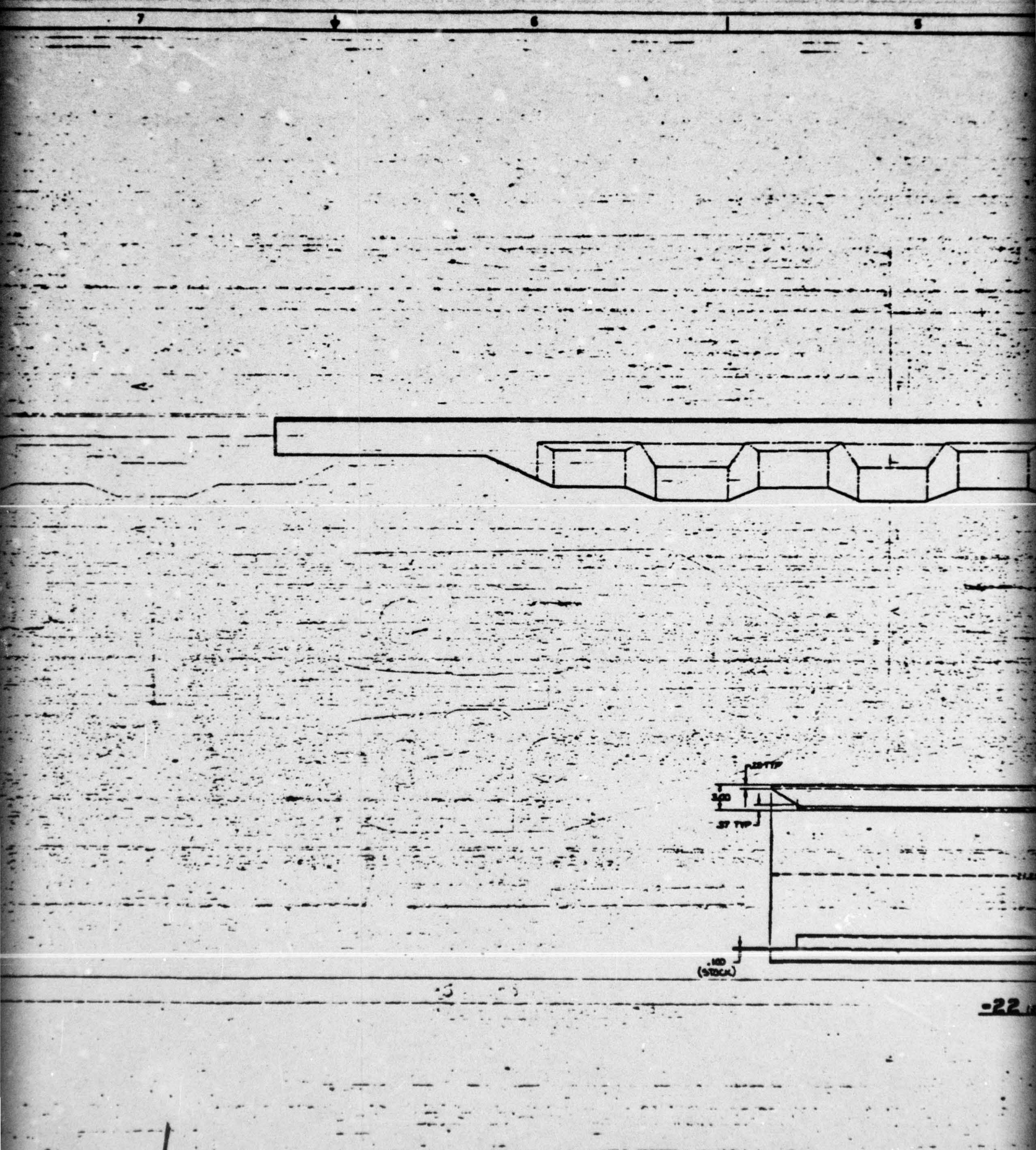
DRILL .125 DIA PILOT HOLE(S)
.500 TYP
.250 TYP
.500 TYP
1.20
2.25
-11 (BRACE)
SCALE 1/1
DRILL .125 DIA PILOT HOLE (15)
.25 CONST FILLET R
1.00 DIA CUTTER RUNOUT (TYP)
1.00R
CHAM .12 x 45°
10.80
4.00
3.00
-13 (WISHBONE)
SCALE 1/1



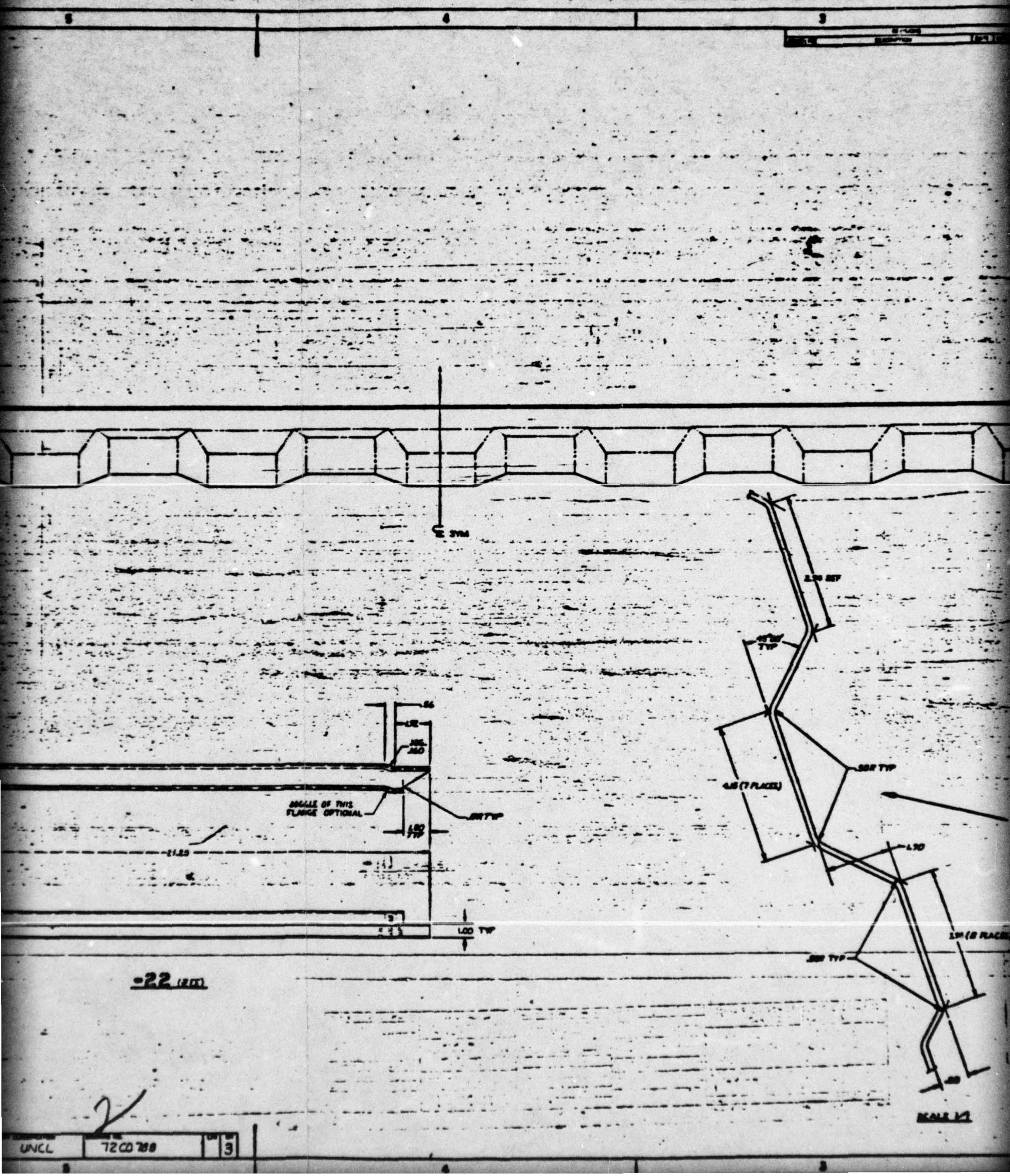
.25 R
2 PLACES
1.00 DIA CUTTER RUNOUT (TYP)
-5 SHOWN
-7 IDENTIC
SCALE 1/1
14170


4.00 REF
3.30
6.30
4.56
1.60 DIA. HOLE
2.47 R
DRILL NO.11 PILOT HOLE (8)
9.50
HOLE PATTERN INTERCHANGEABILITY REQ.
PATTERN MUST BE SYMMETRICAL ABOUT
CTR LINE OF FITTING
-5 SHOWN, -6 OPP (FITTING)
-7 IDENTICAL TO -5 EXCEPT AS NOTED, -8 OPP
SCALE 1/1
-10 (BRACE)
SCALE 1/1

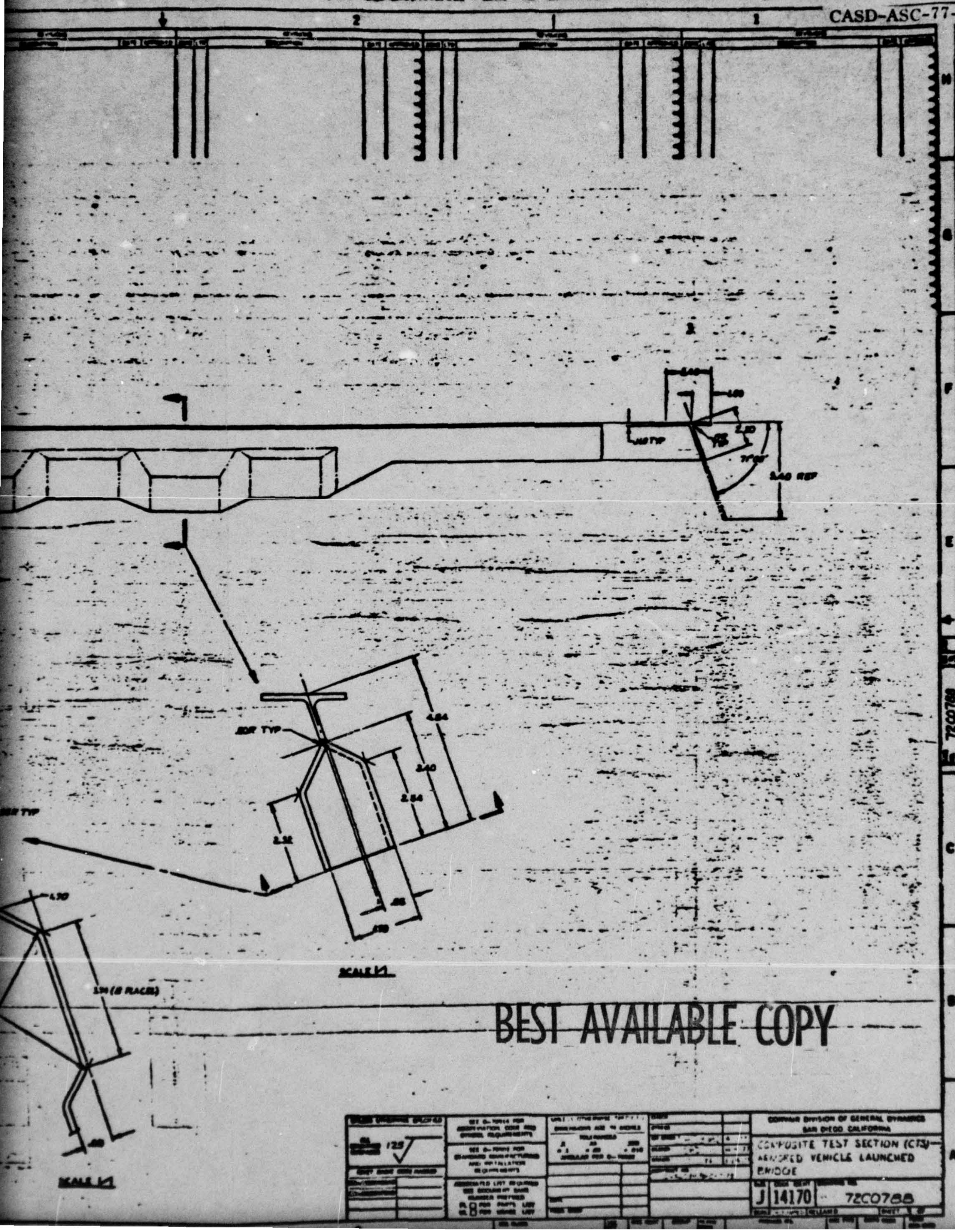

DRILL NO.11 PILOT HOLE (8)
SYM
-10 (BRACE)
SCALE 1/1
BEST AVAILABLE COPY
CONVAIR DIVISION OF GENERAL DYNAMICS
SAN DIEGO, CALIFORNIA
COMPOSITE TEST SECTION (CTS)-
ARMORED VEHICLE LAUNCHED
BRIDGE
J
14170
72C0788
4

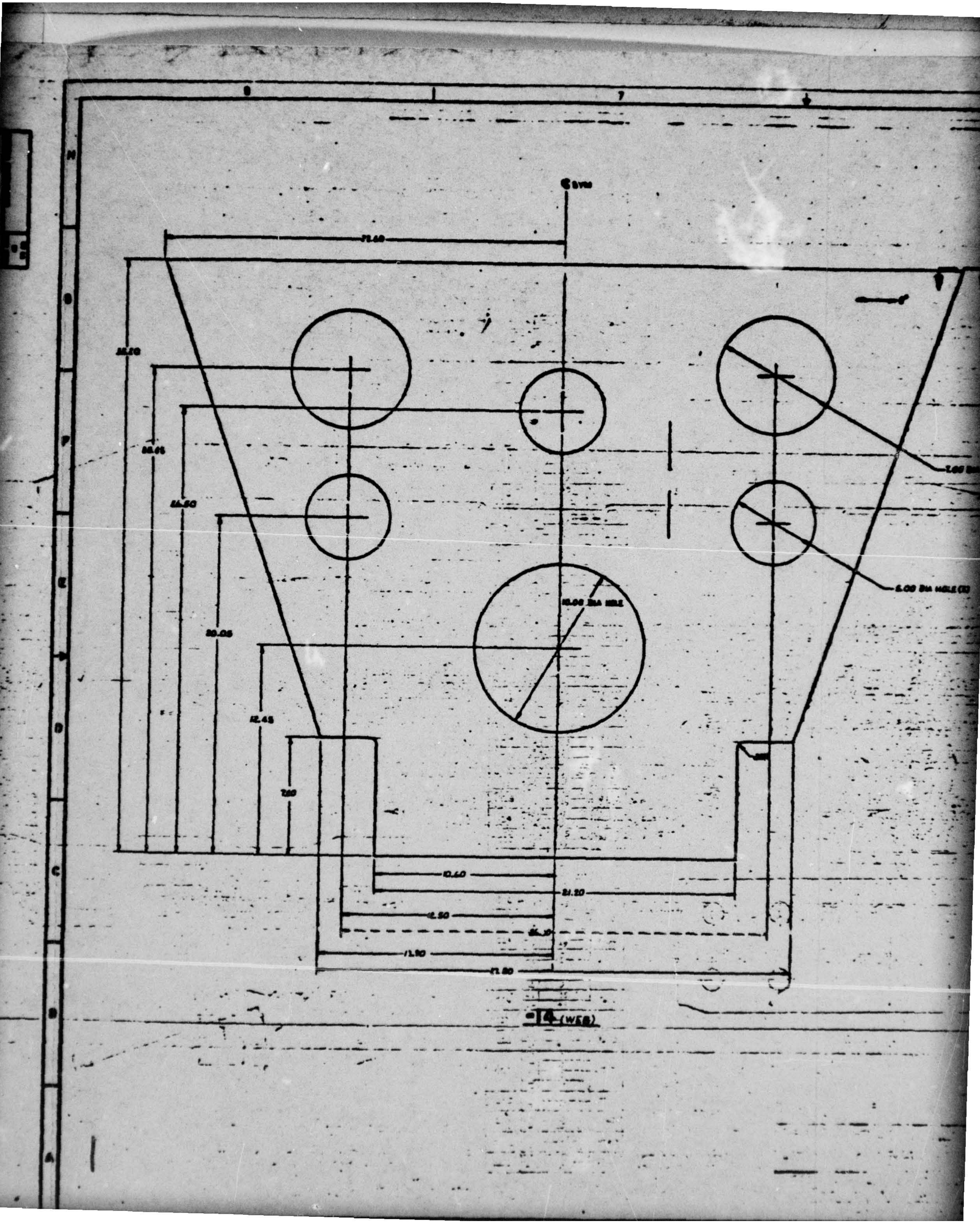


14170	UNCL	72C0788



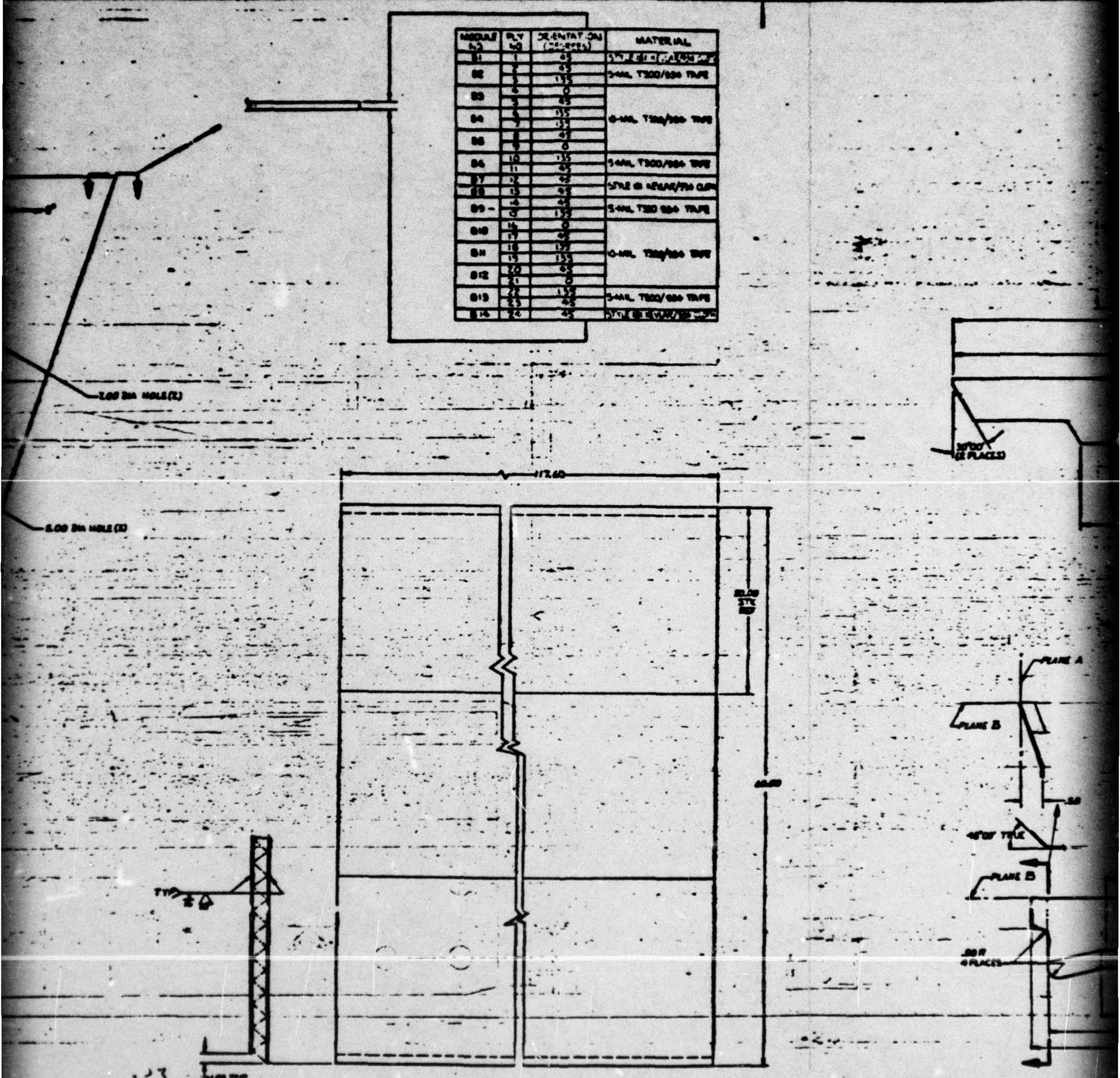
℄ SYM
ANGLE OF THIS FLANGE OPTIONAL
1.00 TYP
-22
SCALE 1/1
UNCL
72C0788
3


2
1
SCALE 1/1
SCALE 1/1
2.40
2.40 REF
4.84
2.40
2.54
2.32
SDR TYP
CONVAIR DIVISION OF GENERAL DYNAMICS
SAN DIEGO CALIFORNIA
COMPOSITE TEST SECTION (CTS)—
ARMORED VEHICLE LAUNCHED
BRIDGE
J
14170
72C0788
72C0788
H
G
F
E
D
C
B
A



10.60
21.20
(WEB)

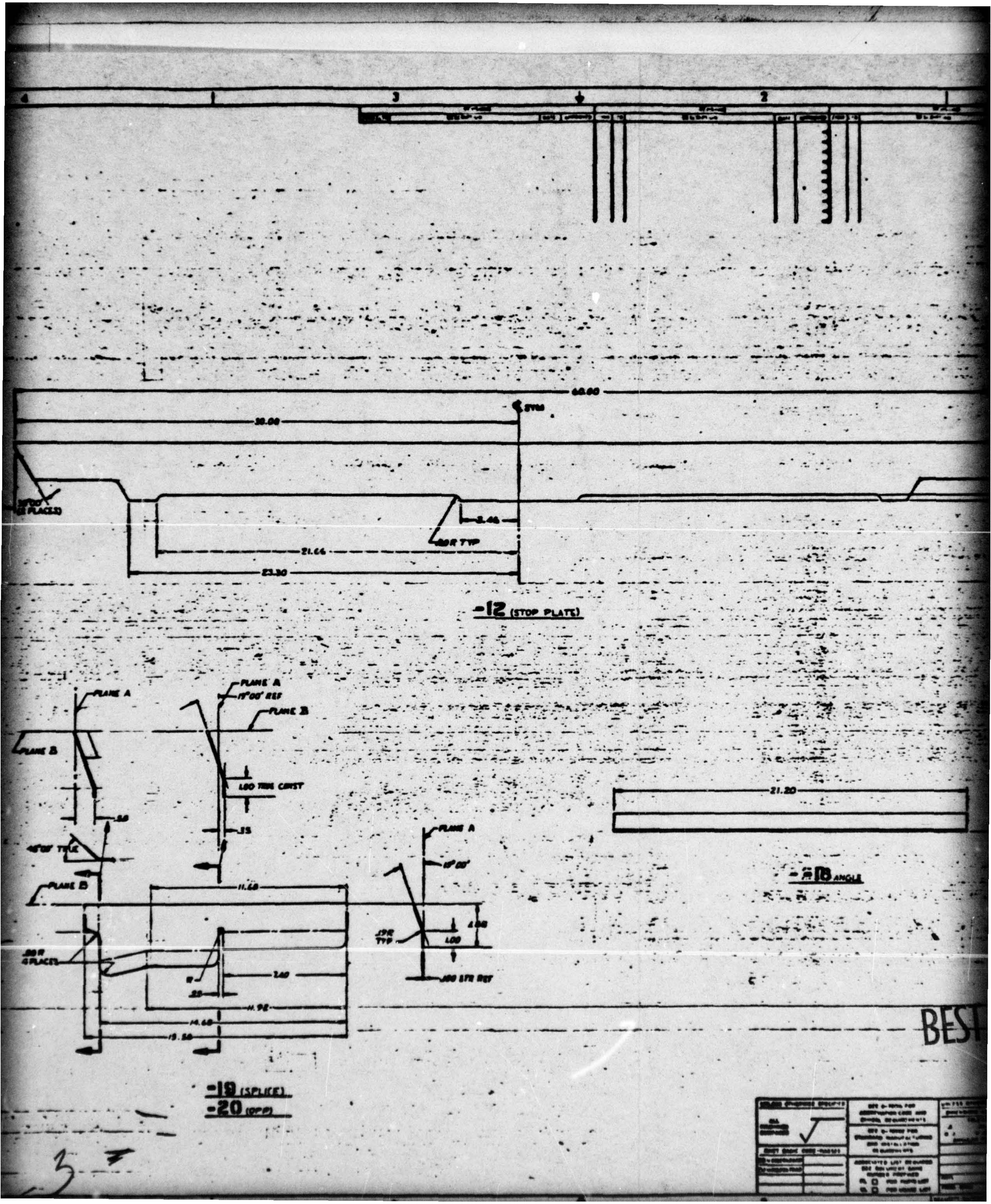
MODULE NO	PLY NO	ORIENTATION (DEGREES)	MATERIAL
B1	1	45	STYLE 181 KEVLAR/934 CLOTH
B2	2	45	5-MIL T300/934 TAPE
	3	135	
B3	4	0	10-MIL T300/934 TAPE
	5	45	
B4	6	135	
	7	135	
B5	8	45	
	9	0	
B6	10	135	5-MIL T300/934 TAPE
	11	45	
B7	12	45	STYLE 181 KEVLAR/934 CLOTH
B8	13	45	
B9	14	45	5-MIL T300/934 TAPE
	15	135	
B10	16	0	10-MIL T300/934 TAPE
	17	45	
B11	18	135	
	19	135	
B12	20	45	
	21	0	
B13	22	135	5-MIL T300/934 TAPE
	23	45	
B14	24	45	STYLE 181 KEVLAR/934 CLOTH

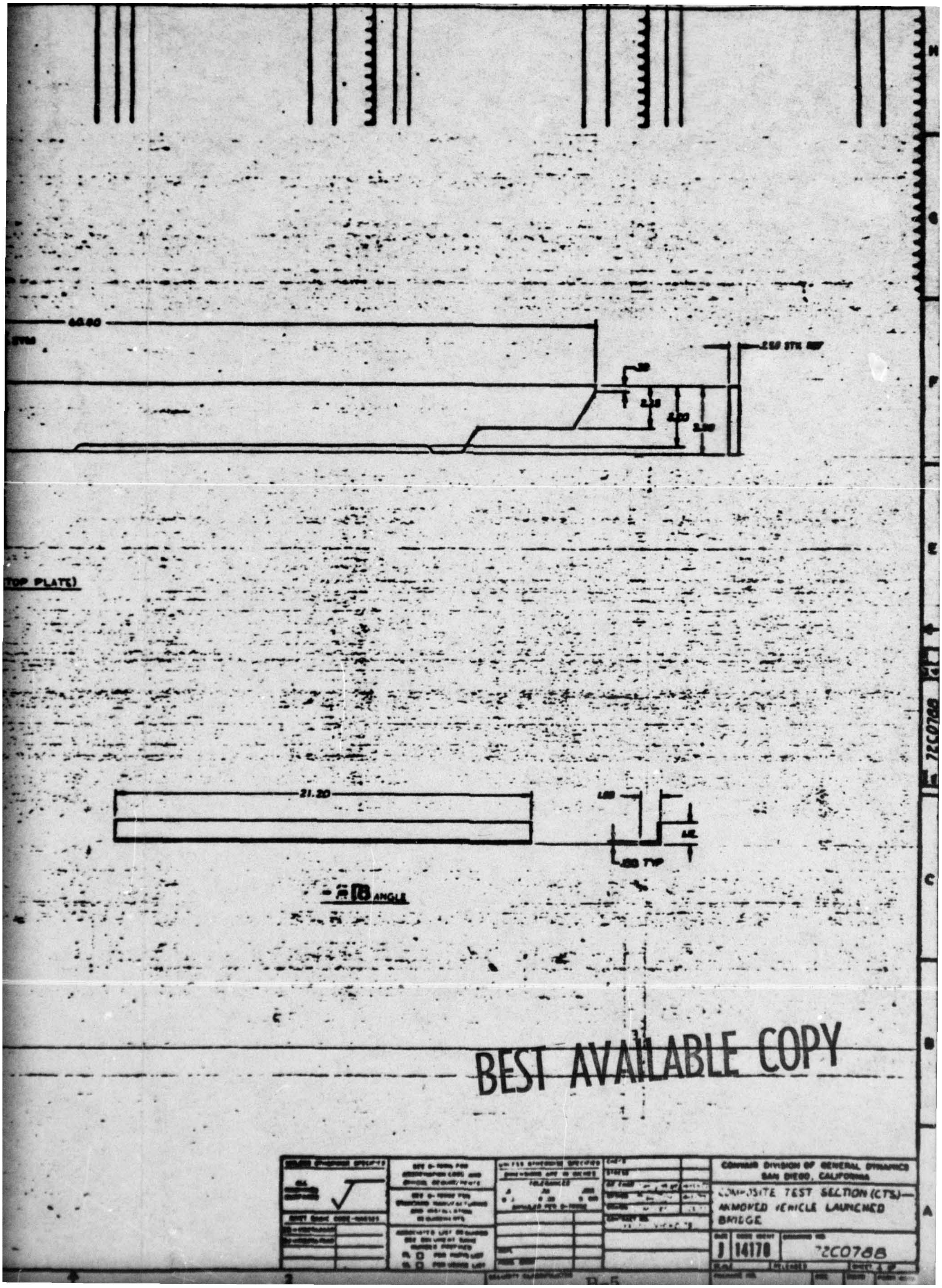


-13 (TREADWAY)
SCALE 1/10

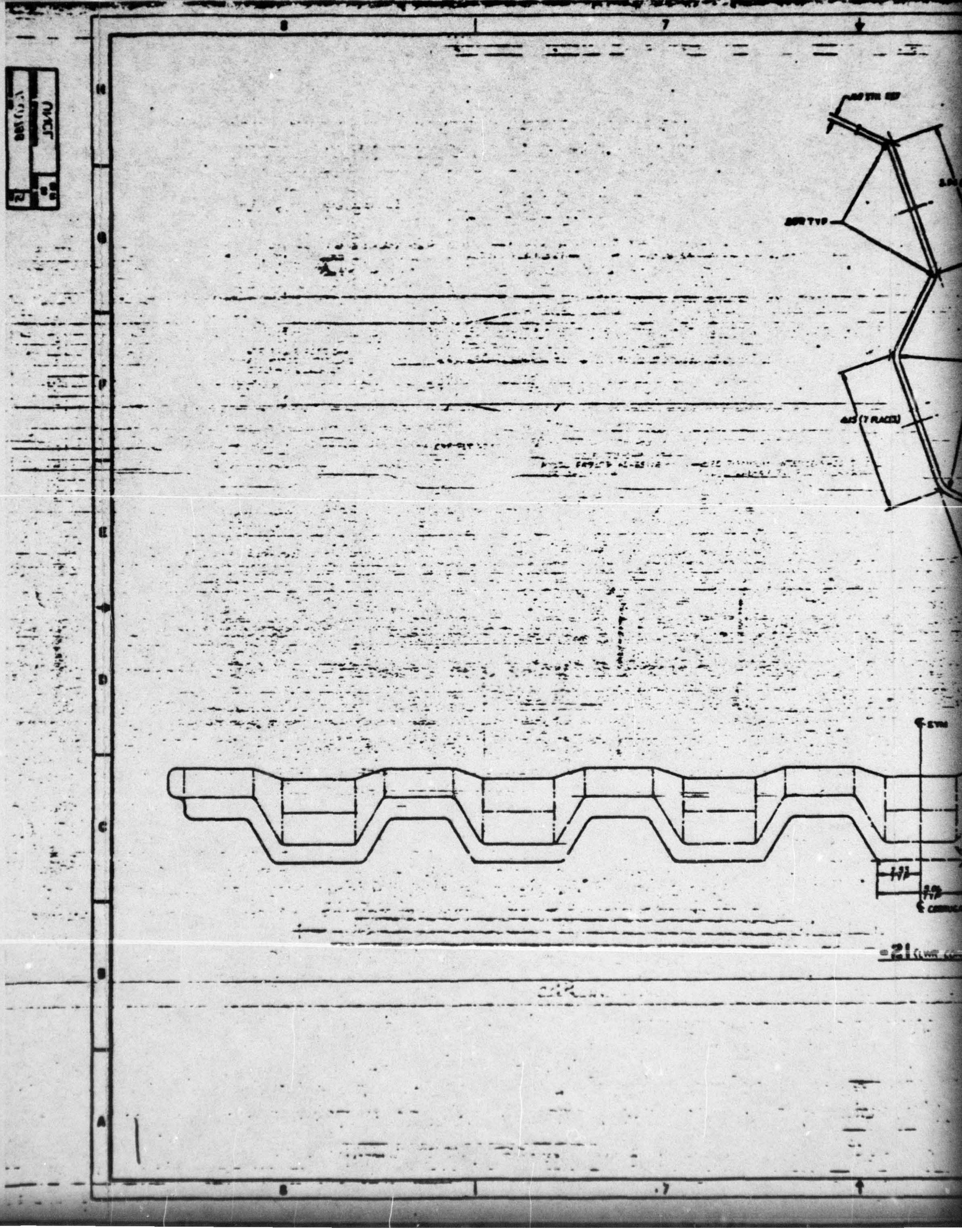
2

14178 | 4


60.00
30.00
3.46
.50R TYP
21.64
23.30
-12 (STOP PLATE)
PLANE A
PLANE B
15°00' REF
1.00 TRUE CONST
.35
.50
45°00' TRUE
11.68
2.60
11.92
14.68
15.50
.19R TYP
1.00
.100 STR REF
21.20
-18 ANGLE
-19 (SPLICE)
-20 (OPP)



60.80
.250 STK REF
2.20
(TOP PLATE)
21.20
.100 TYP
ANGLE
BEST AVAILABLE COPY
CONVAIR DIVISION OF GENERAL DYNAMICS
SAN DIEGO, CALIFORNIA
COMPOSITE TEST SECTION (CTS)—
ARMORED VEHICLE LAUNCHED
BRIDGE
J
14170
72C0788



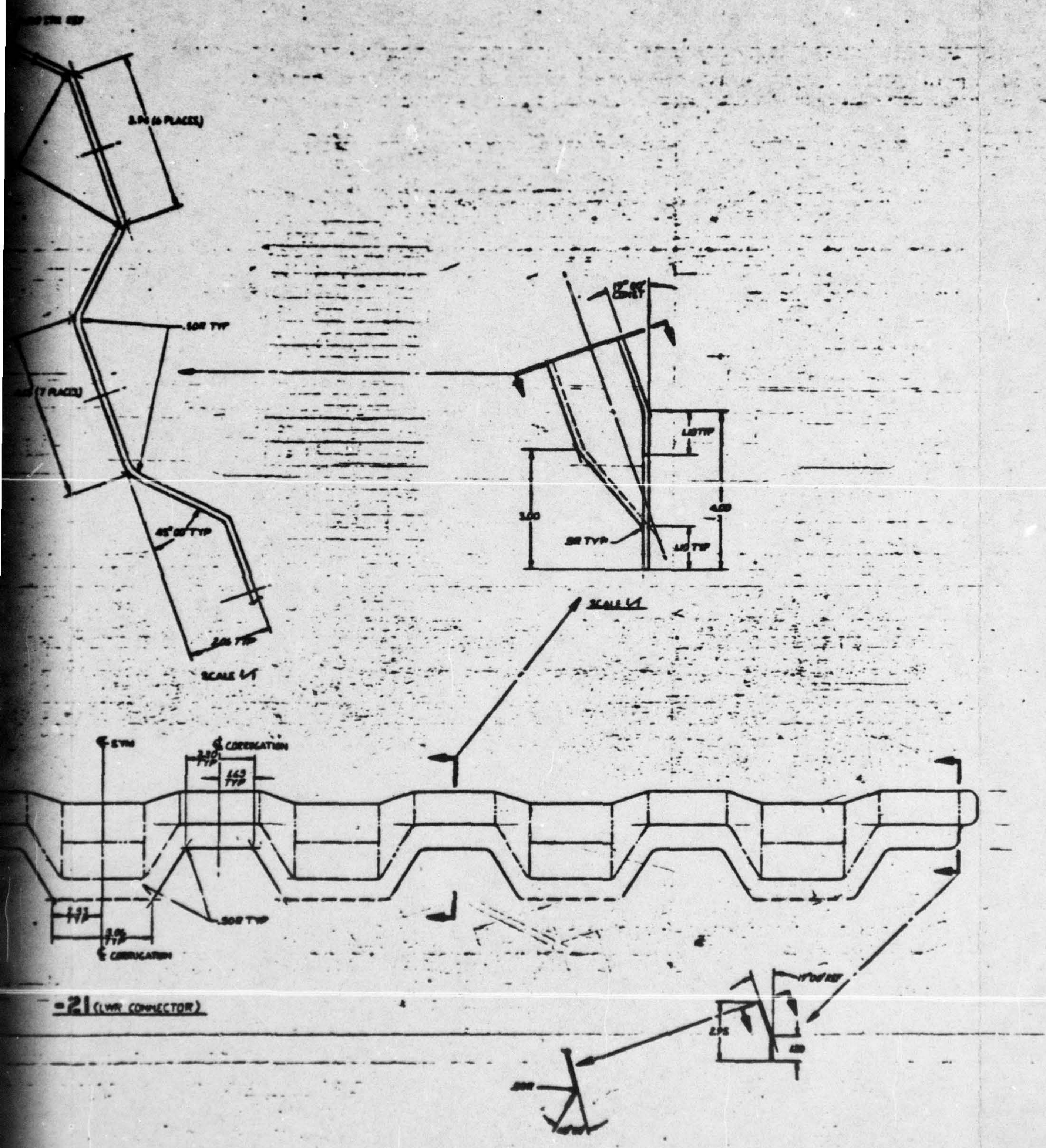
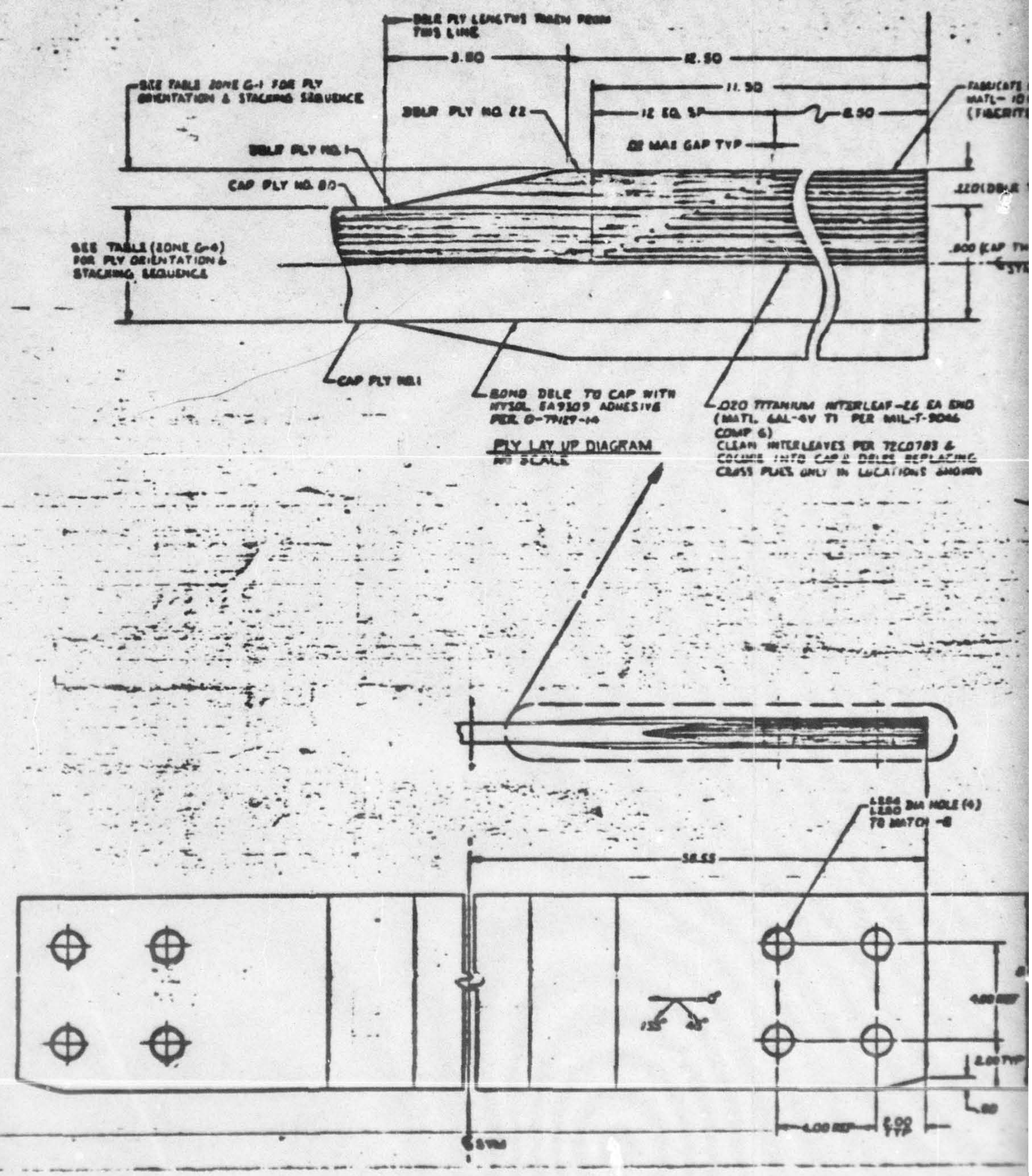


TABLE II

CAP PLY LAY UP

MODULE NO.	PLY NO.	ORIENTATION (DEG)	[illegible]
C1	1	0	[illegible]
	2	0	
C2	3	45	[illegible]
	4	135	
C3	5	0	[illegible]
	6	0	
C4	7	45	[illegible]
	8	135	
C5	9	0	[illegible]
	10	0	
	11	0	
	12	0	
C6	13	45	[illegible]
	14	135	
C7	15	0	[illegible]
	16	0	
C8	17	45	[illegible]
	18	135	
C9	19	0	[illegible]
	20	0	
	21	0	
	22	0	
C10	23	45	[illegible]
	24	135	
C11	25	0	[illegible]
	26	0	
C12	27	45	[illegible]
	28	135	
C13	29	0	[illegible]
	30	0	
	31	0	
	32	0	
C14	33	45	[illegible]
	34	135	
C15	35	0	[illegible]
	36	0	
C16	37	45	[illegible]
	38	135	
C17	39	0	[illegible]
	40	0	
	41	0	
	42	0	
C18	43	135	[illegible]
	44	45	
C19	45	0	[illegible]
	46	0	
C20	47	135	[illegible]
	48	45	
C21	49	0	[illegible]
	50	0	
	51	0	
	52	0	
C22	53	135	[illegible]
	54	45	
C23	55	0	[illegible]
	56	0	
C24	57	135	[illegible]
	58	45	
C25	59	0	[illegible]
	60	0	
	61	0	
	62	0	
C26	63	135	[illegible]
	64	45	
C27	65	0	[illegible]
	66	0	
C28	67	135	[illegible]
	68	45	
C29	69	0	[illegible]
	70	0	
	71	0	
	72	0	
C30	73	135	[illegible]
	74	45	
C31	75	0	[illegible]
	76	0	
C32	77	135	[illegible]
	78	45	
C33	79	0	[illegible]
	80	0	

TABLE II			
CAP PLY LAY UP			
MODULE NO.	PLY NO.	ORIENTATION (DEG)	LENGTH (IN)
C1	1	0	117.10
	2	0	
C2	3	45	97.60
	4	135	
C3	5	0	117.10
	6	0	
C4	7	45	97.10
	8	135	
C5	9	0	117.10
	10	0	
	11	0	
	12	0	
C6	13	45	96.60
	14	135	
C7	15	0	117.10
	16	0	
C8	17	45	96.10
	18	135	
C9	19	0	117.10
	20	0	
	21	0	
	22	0	
C10	23	45	95.60
	24	135	
C11	25	0	117.10
	26	0	
C12	27	45	95.10
	28	135	
C13	29	0	117.10
	30	0	
	31	0	
	32	0	
C14	33	45	94.60
	34	135	
C15	35	0	117.10
	36	0	
C16	37	45	94.10
	38	135	
C17	39	0	117.10
	40	0	
	41	0	
	42	0	
C18	43	135	94.10
	44	45	
C19	45	0	117.10
	46	0	
C20	47	135	96.60
	48	45	
C21	49	0	117.10
	50	0	
	51	0	
	52	0	
C22	53	135	95.10
	54	45	
C23	55	0	117.10
	56	0	
C24	57	135	95.60
	58	45	
C25	59	0	117.10
	60	0	
	61	0	
	62	0	
C26	63	135	96.10
	64	45	
C27	65	0	117.10
	66	0	
C28	67	135	96.60
	68	45	
C29	69	0	117.10
	70	0	
	71	0	
	72	0	
C30	73	135	97.10
	74	45	
C31	75	0	117.60
	76	0	
C32	77	135	97.60
	78	45	
C33	79	0	117.10
	80	0	

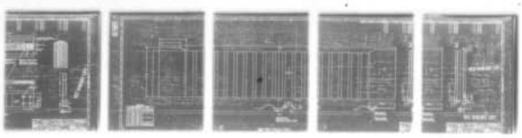


-23 (BEAM)

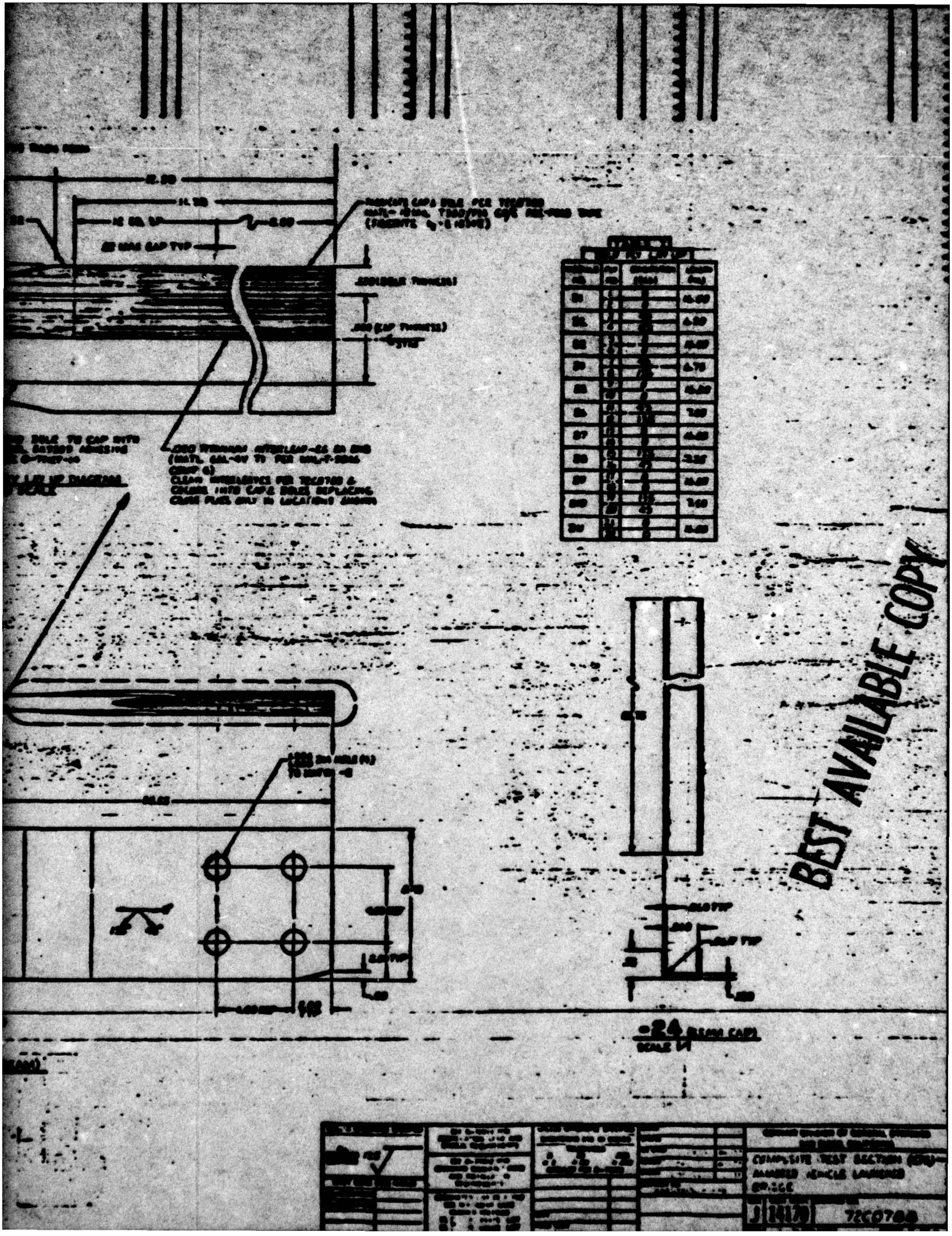
3

AD-A046 949 GENERAL DYNAMICS/CONVAIR SAN DIEGO CALIF F/G 13/13
ADVANCED COMPOSITE ARMY ASSAULT BRIDGE DEVELOPMENT THROUGH SUBC--ETC(U)
JUN 77 DAAG53-76-C-0175
UNCLASSIFIED CASD-ASC-77-002 NL

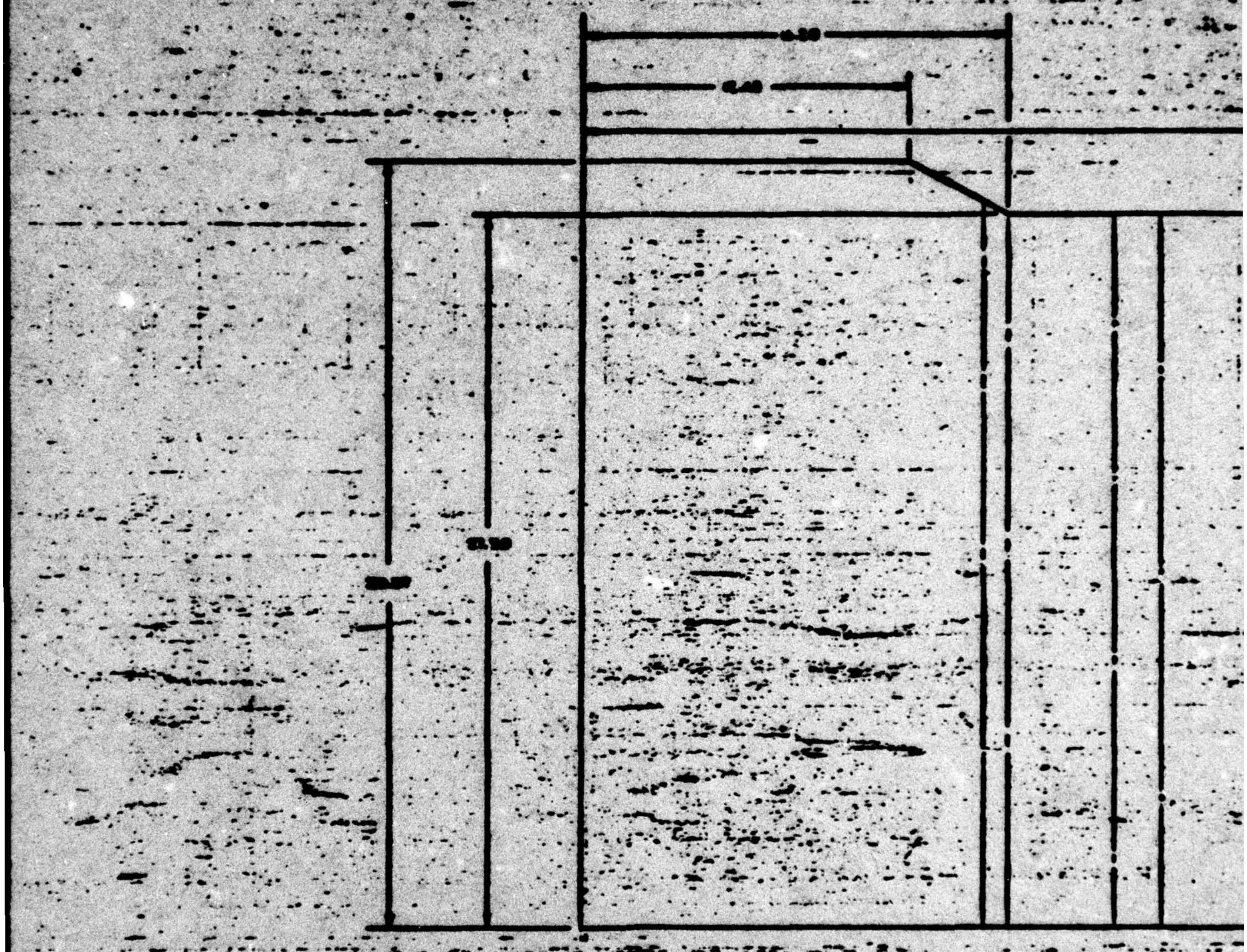
3 OF 3
AD
A046 949



END
DATE
FILMED
1 - 78
DDC

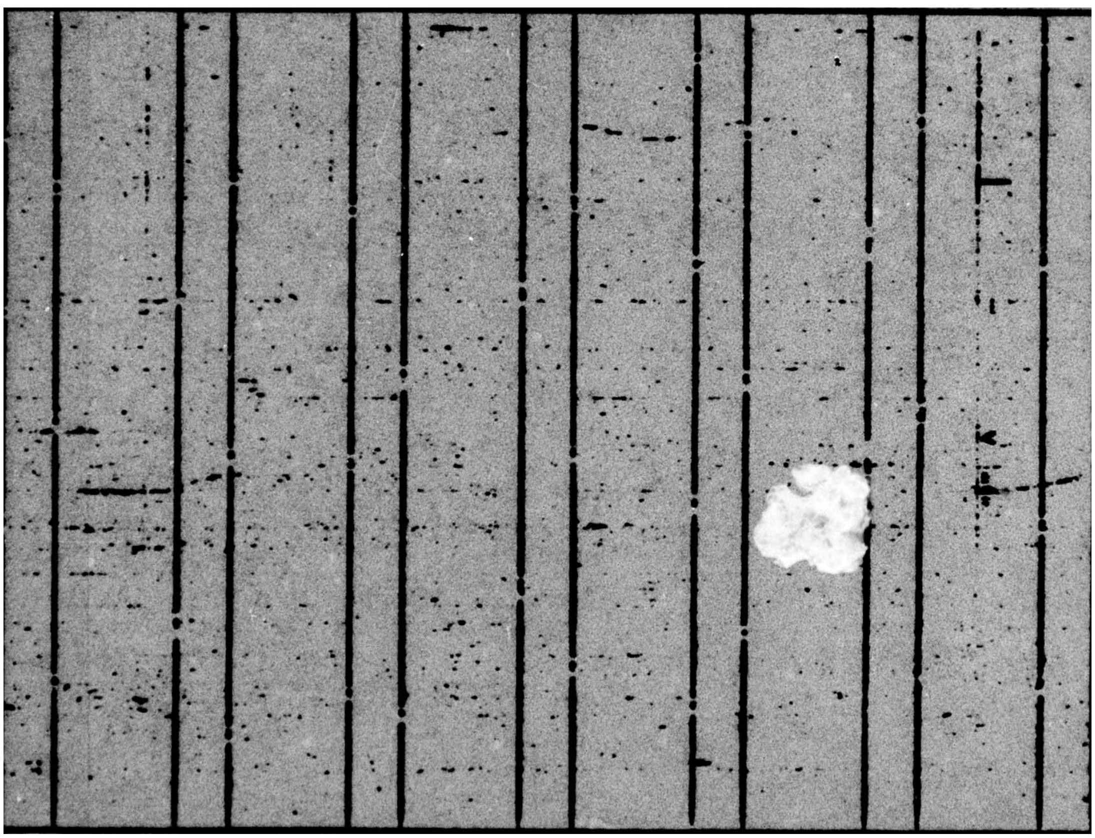


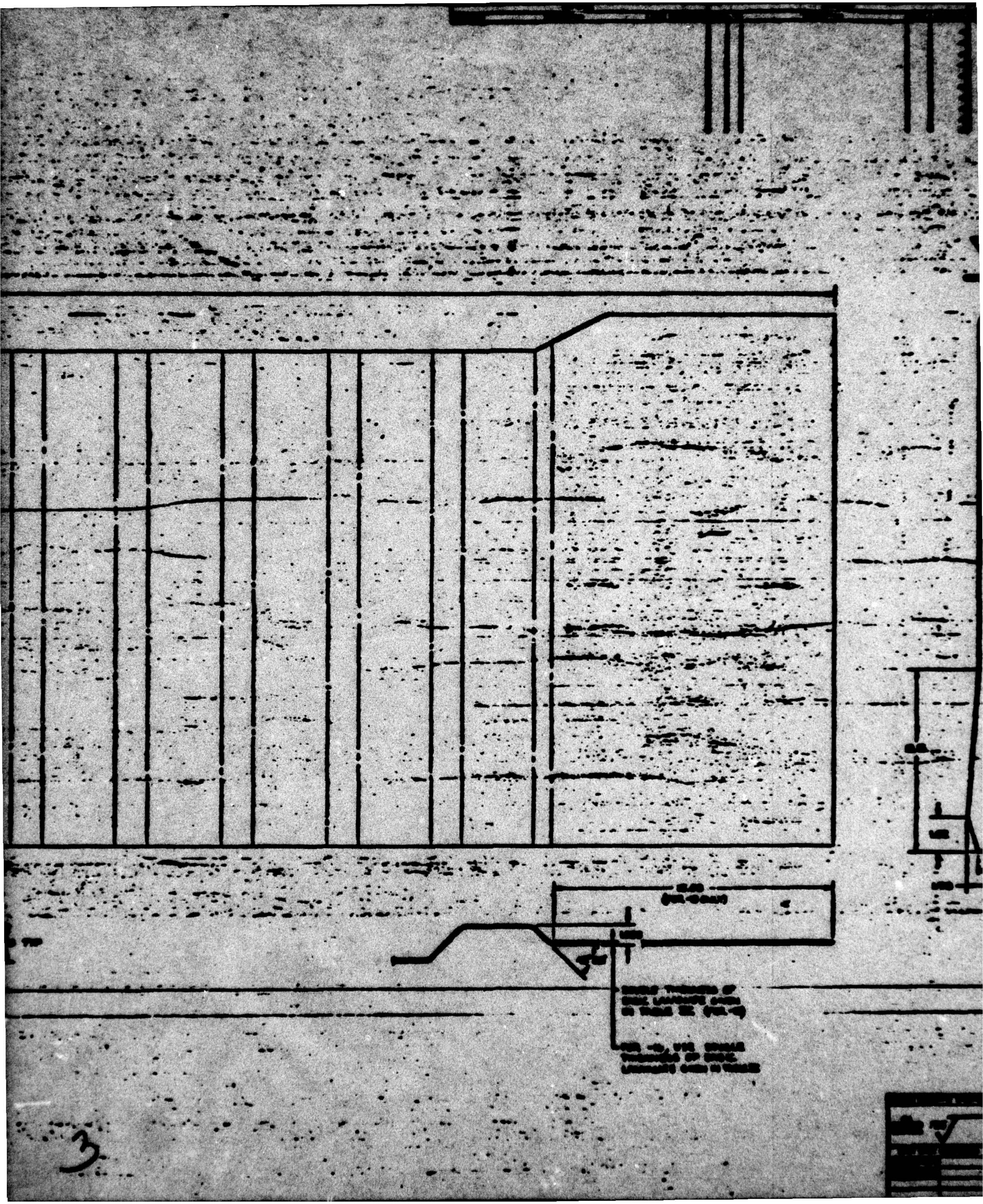
-24 (BEAM CAP)
SCALE 1/1
COMPOSITE TEST SECTION
BRIDGE
72C0788



[illegible]

CORRUGATION PLY ORIENTATION			
[illegible] NO.	PLY NO.	ORIENTATION (DEGREES)	MATERIAL
[illegible]	1	45	[illegible]
[illegible]	2	45	[illegible]
	3	135	
[illegible]	4	0	[illegible]
	5	45	
[illegible]	6	135	
	7	135	
[illegible]	8	45	
	9	0	
[illegible]	10	135	[illegible]
	11	45	
[illegible]	12	45	[illegible]





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